NRTC/RITA FAA Rotorcraft Damage Tolerance Project

Presented by
Dr. Sohan Singh
Bell's Principal Investigator

- Bell – Dr. Sohan Singh (PI)
- Boeing – Bill Weiss (PI)
- Sikorsky – Dr. John Wang (PI)

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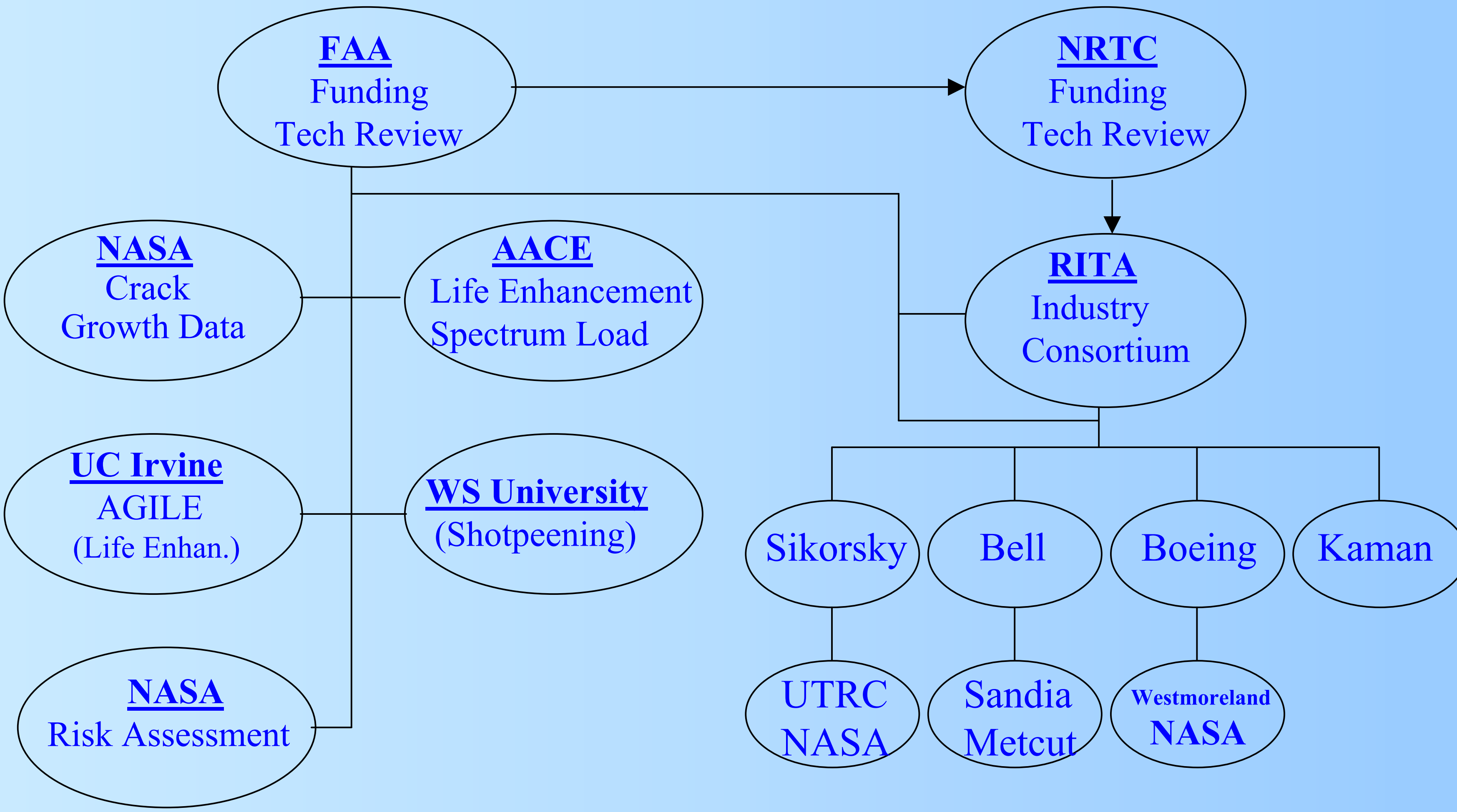
FAA Rotorcraft Metals Structural Integrity Program



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RITA/FAA Technical Objectives

- Cooperative RITA research program based on the “RCDT Roadmap”

- Develop the technology and data to adopt crack growth damage tolerant design, certification, and management for rotorcraft in accordance with evolving FAA and DoD requirements

- Efforts will be leveraged based on prior technology and data developed for fixed wing aircraft and engines, modified and expanded to meet the unique requirements of rotorcraft

Report/Document List

- NRTC/RITA Reports: Tech plans, quarterly reports, year end reports and reviews

- Technical Reports: Individual RITA reports documenting technical work and results for each task. (Non-proprietary pending TAC approval)

- Data Packages: data, codes and supporting Tech Reports (NRTC/RITA Proprietary)

- Specific Issues Report: Joint RITA report on rotorcraft DT issues and guidance to address the issues. (Non-proprietary pending TAC approval)

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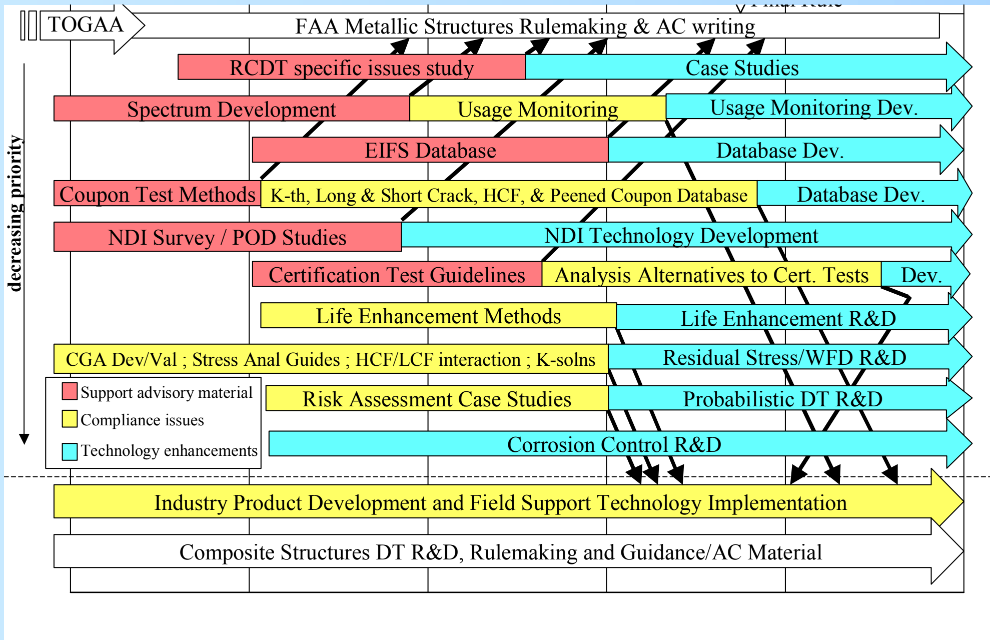
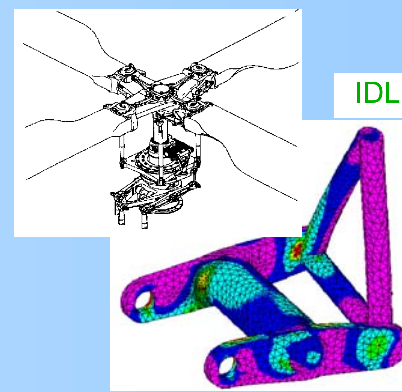
Rotorcraft Damage Tolerance (RCDT) Program

Objective – Develop and validate technology for the transition from safe-life to damage tolerant design, verification, and management of rotorcraft structure needed to meet future FAA and military requirements.

ROTORCRAFT DAMAGE TOLERANCE (RCDT) ROADMAP



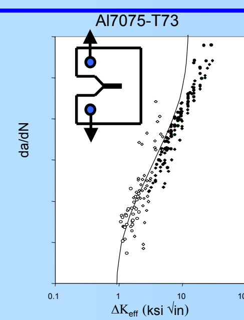
CRACK GROWTH ANALYSIS VALIDATION



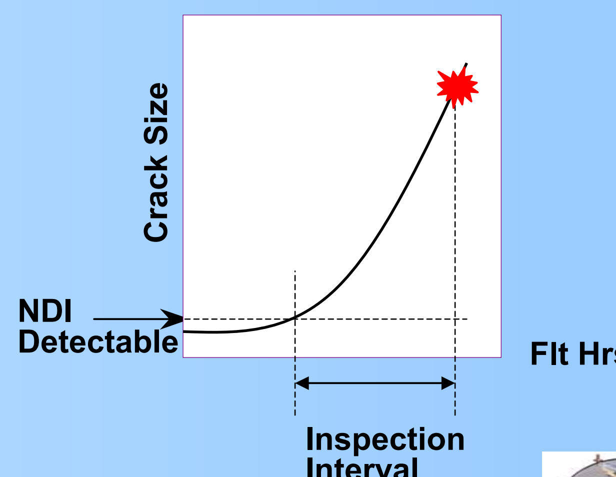
IDLER LINK

FEM MODEL

NDI



CRACK GROWTH DATA



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List of RCDT Roadmap Research Areas (RA) Indicating the Level of Effort by RITA Principal Members

RITA/FAA RCDT R&D Roadmap Areas	**RITA members R&D role M = Major and S = Supporting**		
	Bell	Boeing	Sikorsky
1) RCDT specific issues study	**M**	**M**	**M**
2) Spectrum development and usage monitoring	**M**	**M**	S
3) Equivalent initial flaw sizes (EIFS)	S	S	**M**
4) Crack growth material database	**M**	S	**M**
5) Nondestructive inspection/evaluation (NDI/E)	**M**	S	S/**M**
6) Certification testing	M	M	M
7) Life enhancement methods	S	S	**M**/S
8) Crack growth analysis (CGA)	**M**	**M**	**M**
9) Risk assessment methods	**M**	**M**	**M**
10) Corrosion control	**M**	M	**S**

Tan color indicates Roadmap areas for program year 2004

➢ **Reference:** Cronkhite, J., Harrison, C., Tritsch, D., Weiss, W., Rousseau, C., "Research on Practical Damage Tolerance Methods for Rotorcraft Structures" presented at the American Helicopter Society 56th Annual Forum, Virginia Beach, Virginia, May 2-4, 2000.

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Bell Tasks

TASK	2000	2001	2002	2003	2004	2005
RA 1: Specific Issues and Case Studies						
RA 2: Spectrum Development and Usage Monitoring						
RA 4: Crack Growth Testing						
RA 5: NDI/E Corrosion & Crack Detection Methods						
RA 6: Certification Testing					Coupon Element	Component
RA 8: Crack Growth Analysis Evaluation/Validation						
RA 9: Risk Assessment / Probabilistic Methods						
RA 10: Corrosion Control						

Tan color indicates Roadmap areas for program year 2004

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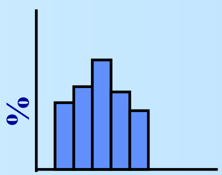
Bell - Technical Objectives

- RA 1: Identify the unique issues and DT technology to address those issues for rotorcraft structures and develop a DTA full-scale component demonstration
- RA 2: Develop a stress spectrum for element level coupons of a main rotor yoke PSE and evaluate RITA ground station software using operational data
- RA 4: Develop crack growth threshold and da/dN crack growth data for commonly used materials using surface crack specimen
- RA 5: Investigate field inspection NDI methods needed to implement a structural integrity program for corrosion & crack detection (joint effort with Sandia AANC)
- RA 8: Evaluate crack growth analysis code AGILE and attend two workshops
- RA 9: Conduct feasibility study of using Probabilistic Methods (PM) on analyzing a dynamic component

RA 1: Specific Issues Study

➢ MAIN ROTOR YOKE PSE DEMONSTRATION COMPONENT

Individual Aircraft Monitoring



Condition

Events:

GAG

Autorotations

Heavy Lifts

Aircraft Usage Spectrum

(RA 2)

Component Load Spectrum

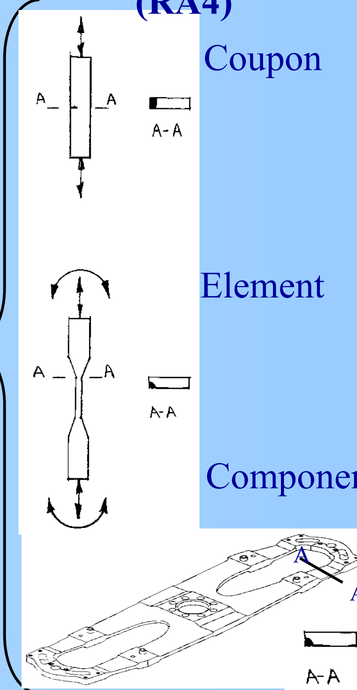
Critical Area Stress Spectrum

Testing Program (RA4)

Coupon

Element

Component



- Fleet Database
- Design Usage Spectrum
- Special Operations

➢ Validation of DTA Analysis Methodology

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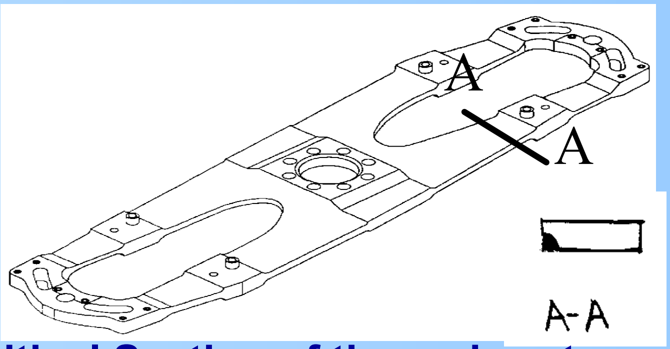
RA 2: Spectrum Development and Usage Monitoring

Stress Equation for a Main Rotor Yoke:

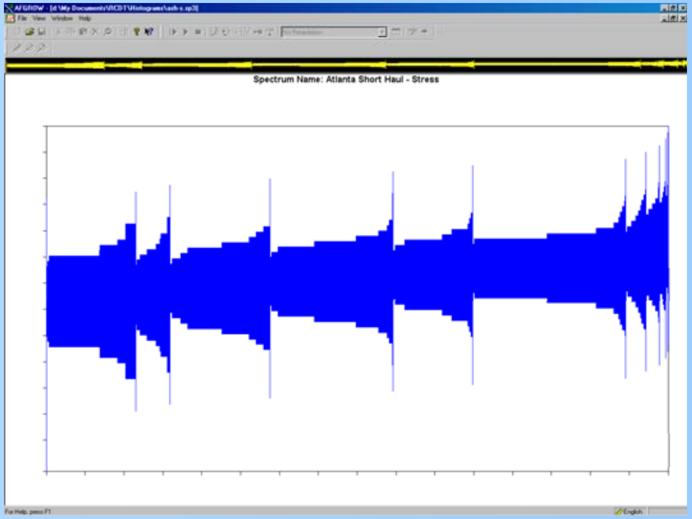
Stresses were calculated at the critical crack location based on a combination of beam bending, chord bending and CF:

$$\text{Stress} = M_b c/I_b + M_c c/I_c + CF$$



Critical Section of the main rotor yoke

- Four usage spectra are used:
  - Certification
  - Atlanta Short Haul
  - Gulf Coast
  - External Loads Survey



Stress Spectrum for Atlanta Short Haul

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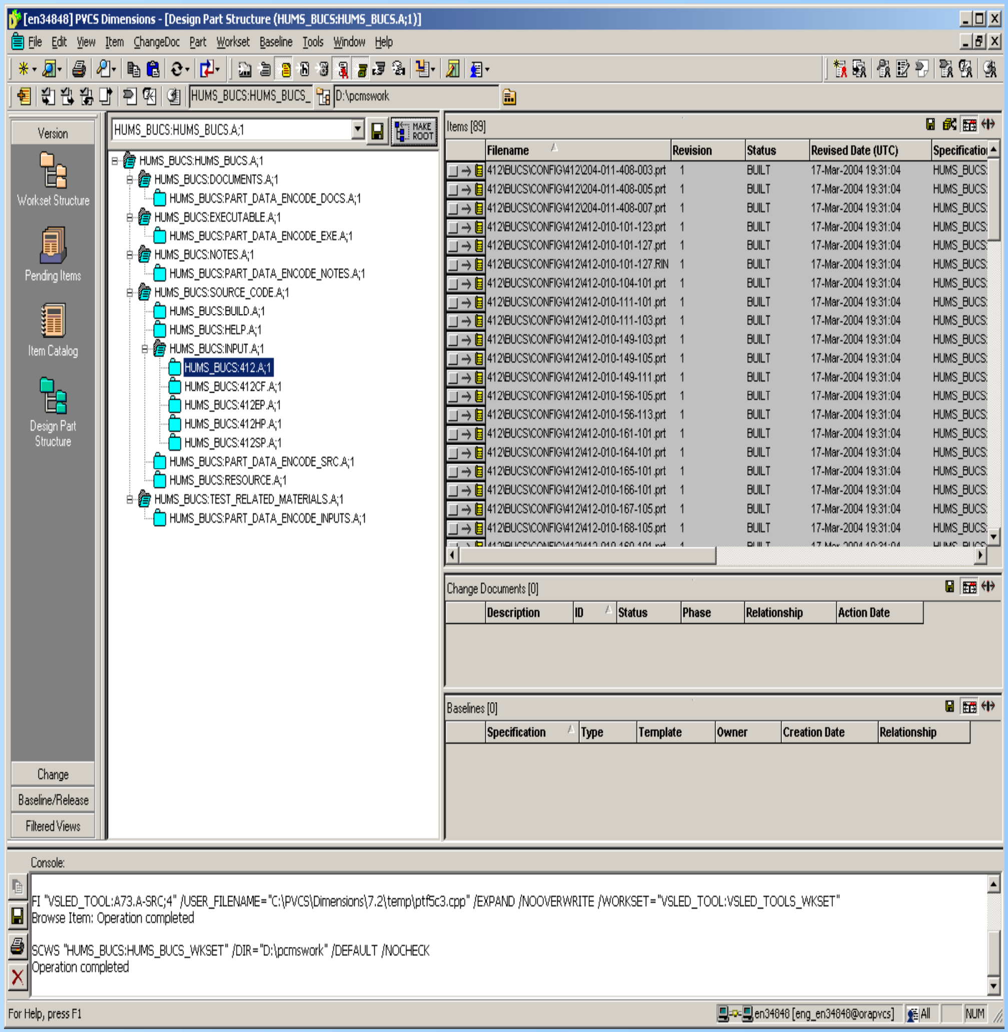
RA 2: Spectrum Development and Usage Monitoring

Usage Monitoring:

- Collected Usage Data on two different B412 aircraft at PHI
- Received Operational Data from a squadron of B412 (CH-146) aircraft from the Canadian Forces
- Installed a first release of RITA Ground Station Software on Bell Ground Station
- Completed a preliminary evaluation of Prototype RITA Ground Station software using the Canadian Forces Data
- PHI Usage Data from 2 aircraft was evaluated with Bell Usage Credit Software (BUCS)



Snapshot of BUCS Input

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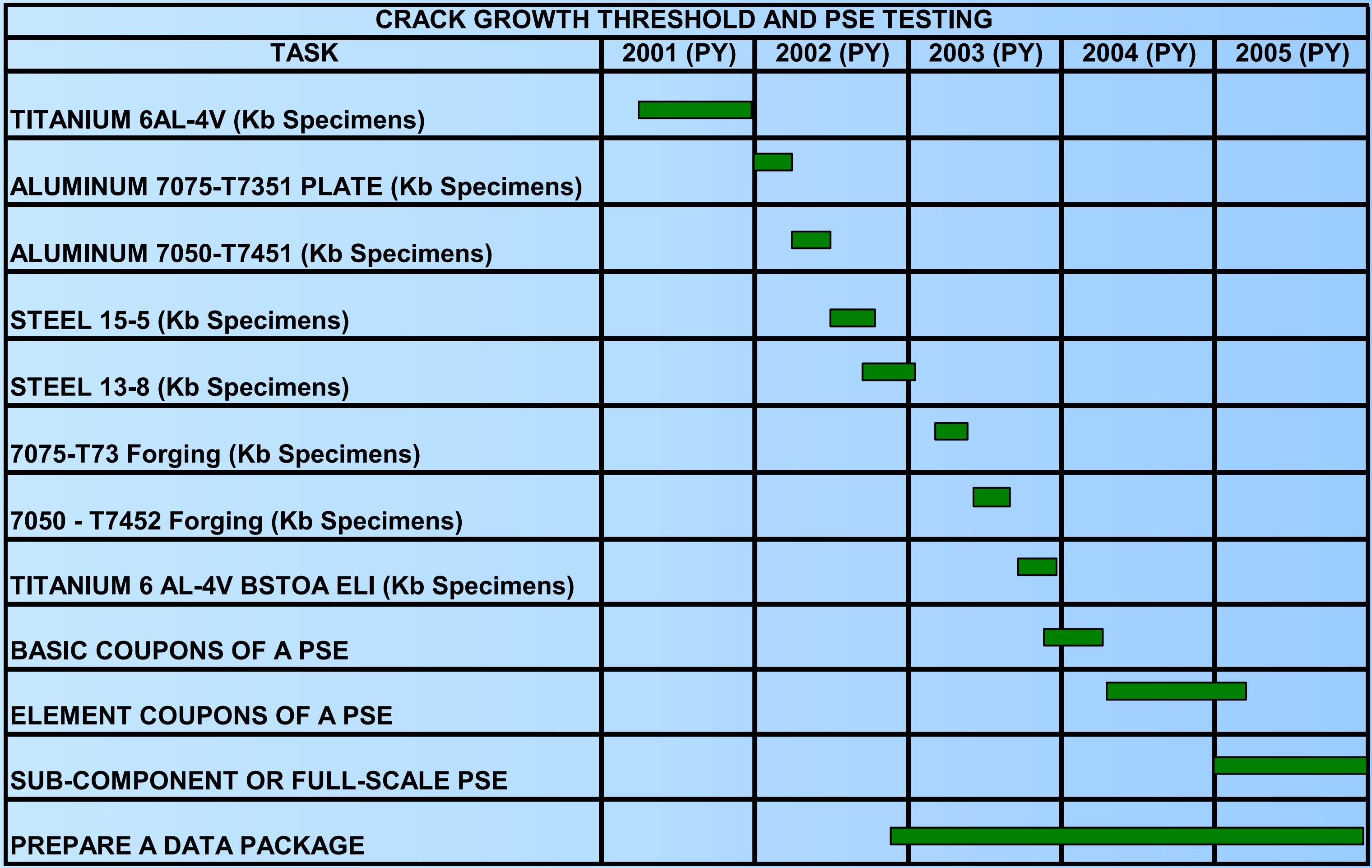
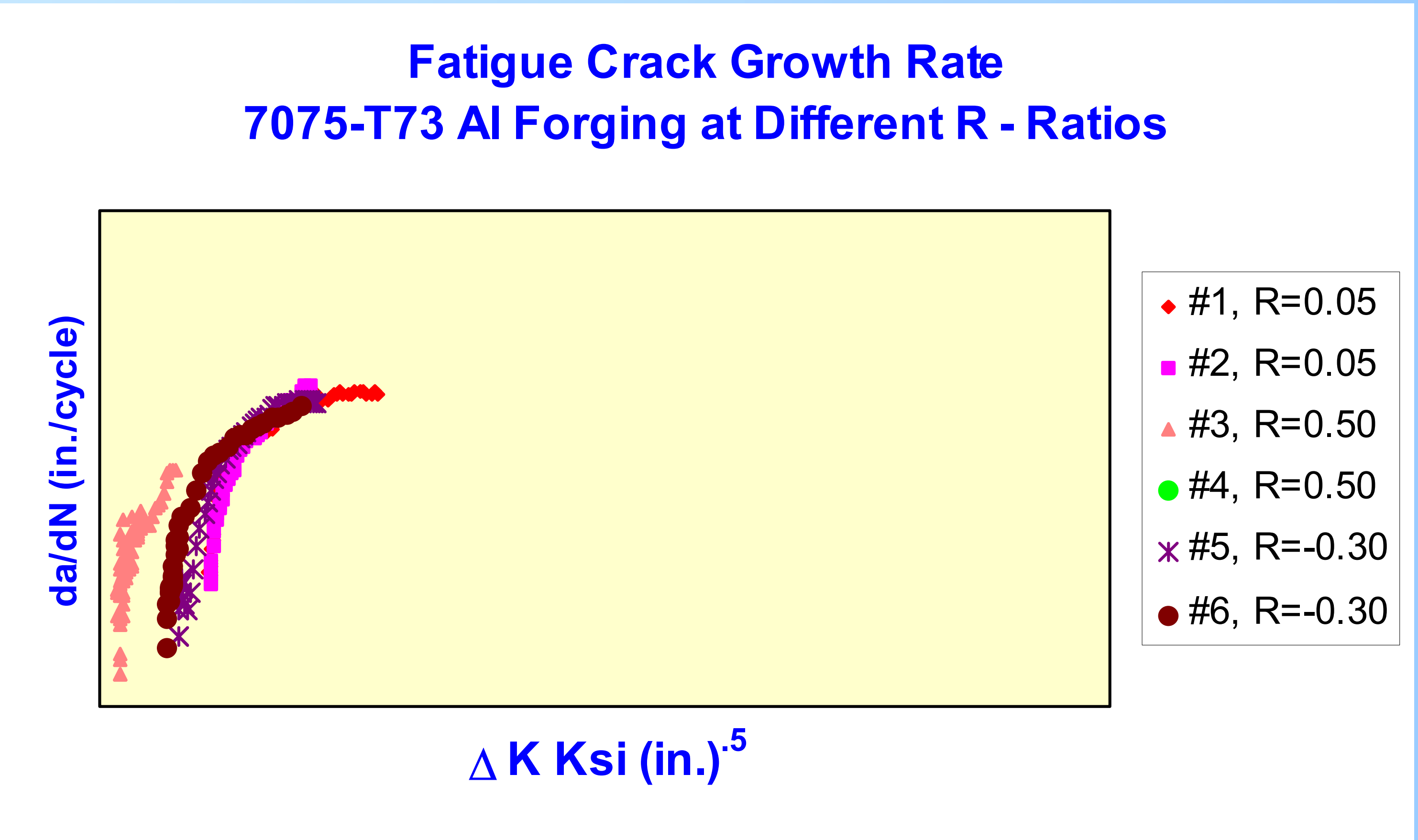
RA 4: Crack Growth Material Testing - Schedule



RA 4: Crack Growth Material Testing

- Example of Kb Bar Crack Growth Threshold Test Data

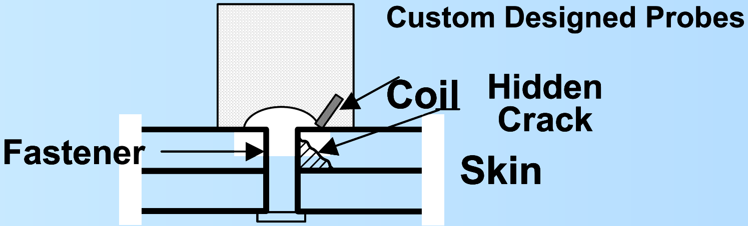


RA 5: NDI Technology Development

➢ Bell & Sandia AANC Joint Effort, Beta Test Site at PHI

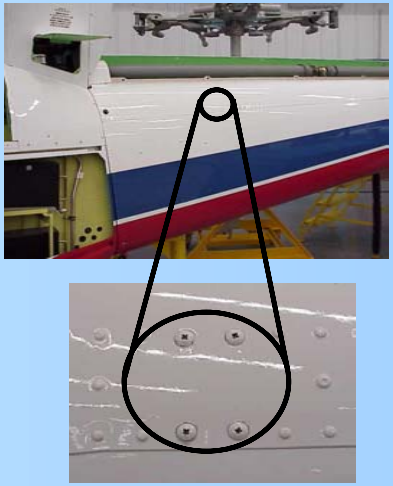
Probe Evaluation

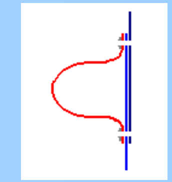
- Provided technical support for custom designing of the probes
- Investigated the origin and effect of inspection variables caused by manufacturing processes, materials, and environmental conditions
- Designed and fabricated panels with cracks introduced by fatigue to simulate real field conditions



Applications

- Fatigue cracking of the tailboom longeron. Hard to detect until the majority of the cross section has cracked
- Developed the calibration panels to develop the inspection techniques
- Plan to evaluate at Beta Test Site



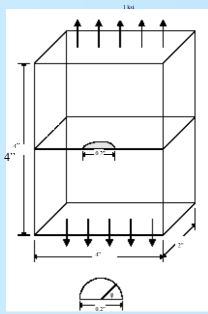


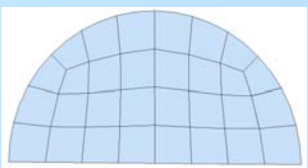
Longeron Cross-Section

RA 8: Crack Growth Analysis

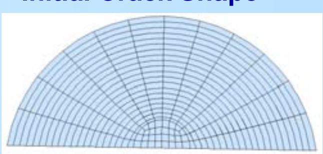
AGILE EVALUATION WORKSHOP I

1. **A 4”X2”X4” rectangular block with semicircular surface crack of 0.1” under tensile load**
2. **A 4”X2”X4” rectangular block with corner crack of 0.1” radius under tensile load**
3. **A 1”X6”X0.5” thick plate with 0.2” long through thickness edge crack under tensile load**
4. **A thick cantilever tube (OD=4”, ID=2”, L=24”) with a semicircular crack of 0.2” radius located at 14” from the free end. The applied load is axial load, moment, shear and torque. These loads will be applied as individual loads and finally as various combinations of axial load, moment, shear and torque load.**
5. **A 5”X8”X5” rectangular bar with an embedded crack of 0.5” radius**



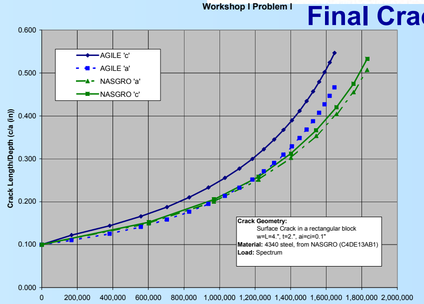


Initial Crack Shape

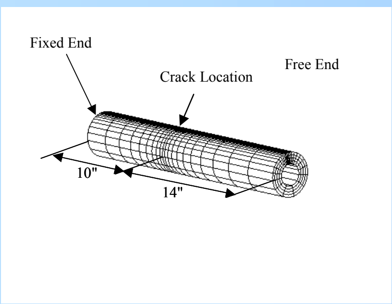


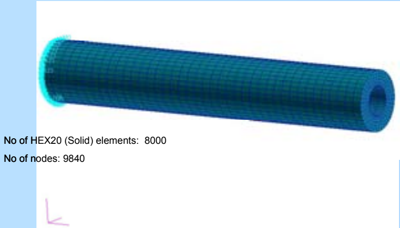
Final Crack Shape

Workshop I Problem I

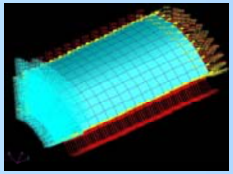


Problem – 1: Surface Crack

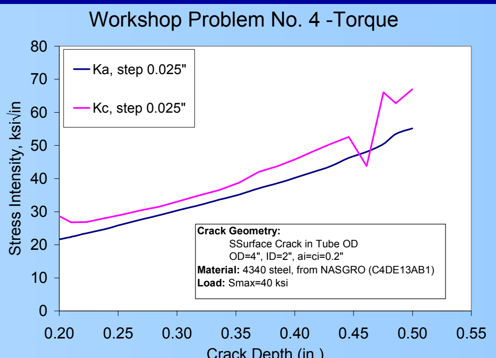


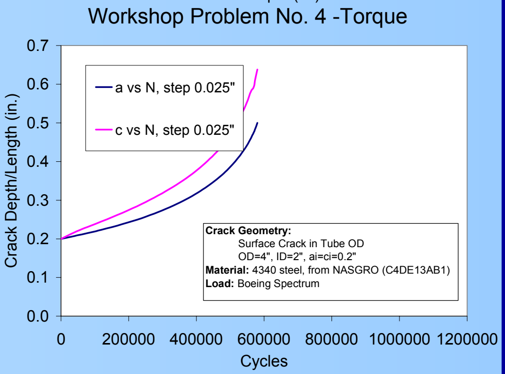


Global Model



Local Model



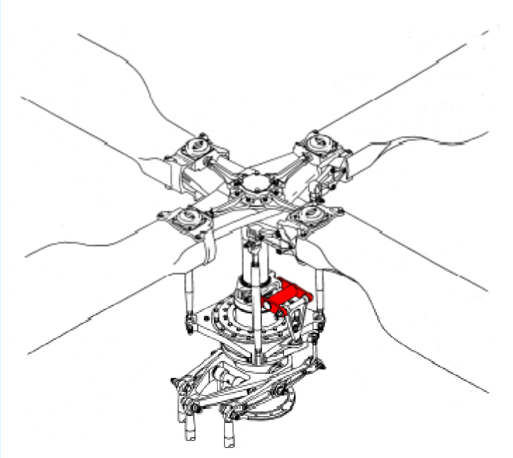


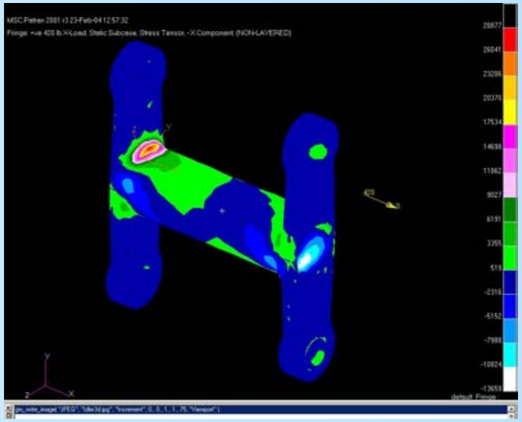
Problem – 4: Tube with a Surface Crack

RA 8: Crack Growth Analysis

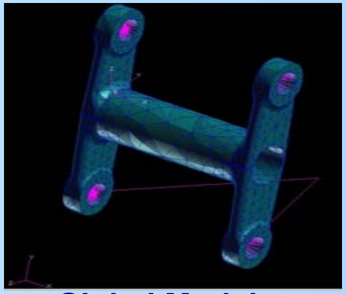
AGILE EVALUATION WORKSHOP II

IDLER LINK CORRELATION

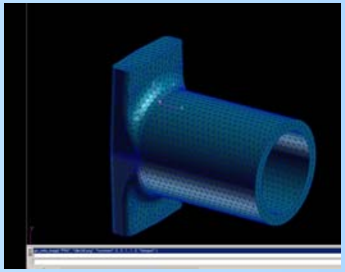




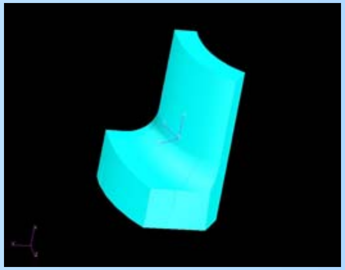
Idler Link - FEM



Global Model



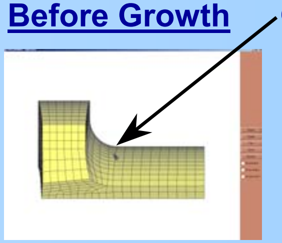
Intermediate Model

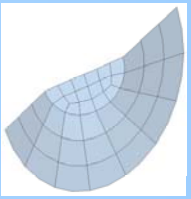


Local Model

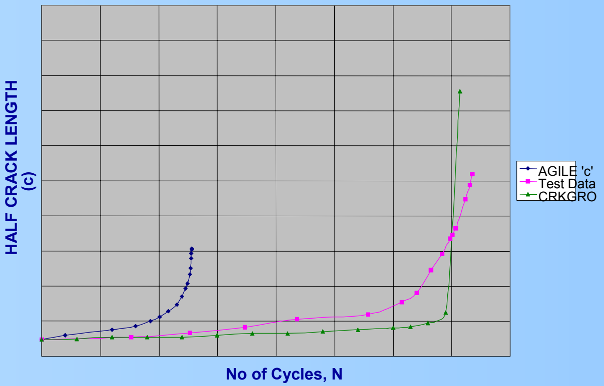
Non-planar Surface Crack

Before Growth





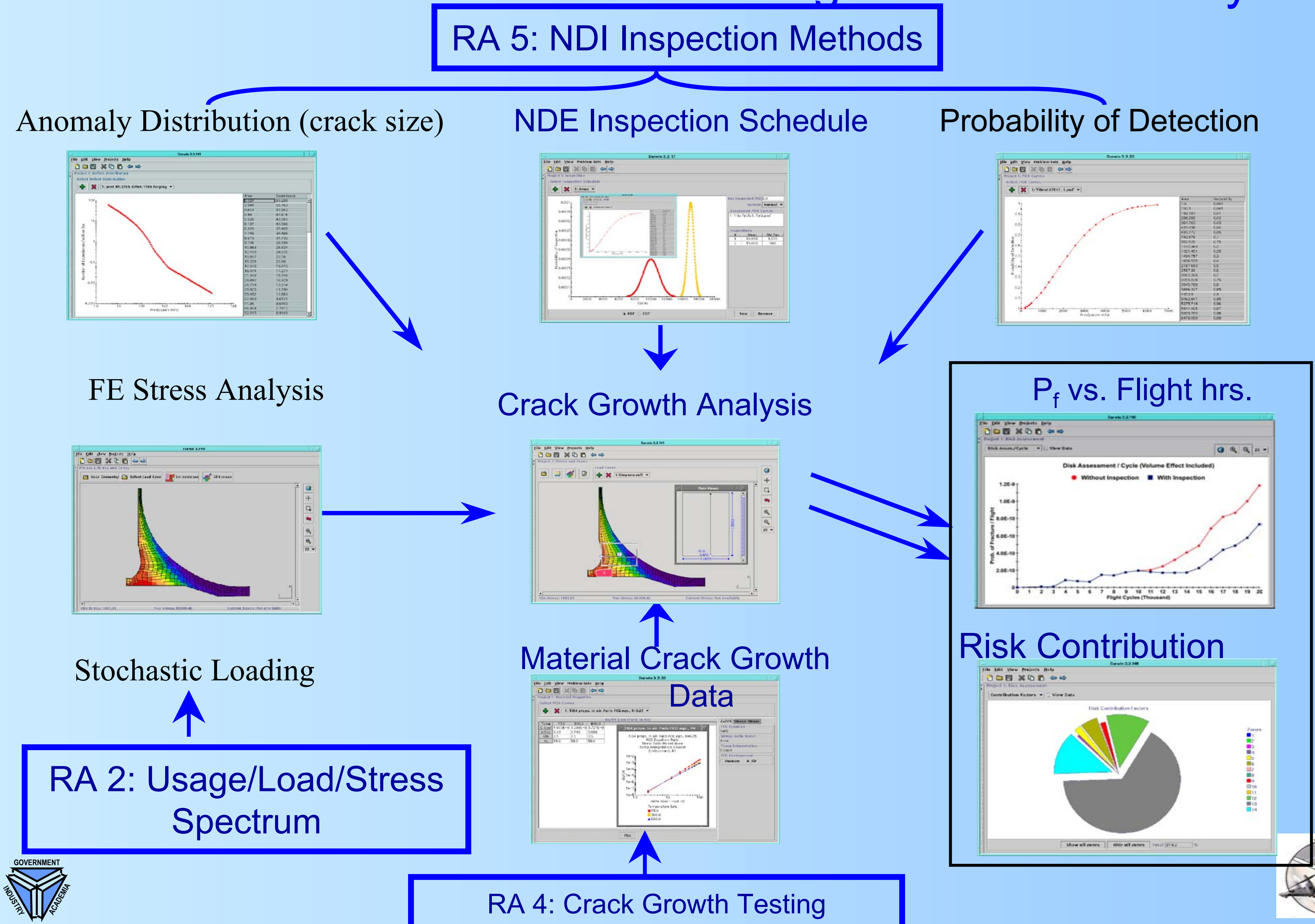
After Growth



Note:

1. Material 7075-T73 Aluminum
2. Walker Equation used
3. CRKGRO results use strain gage data from the test

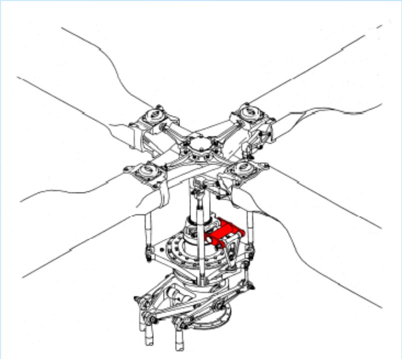
Framework for Probabilistic Damage Tolerance Analysis



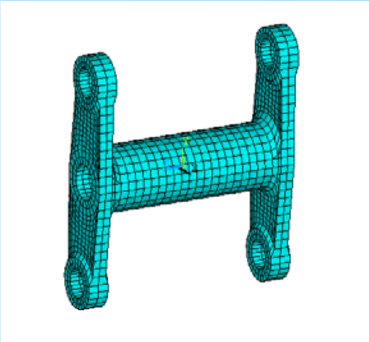
RA 9: Risk Assessment

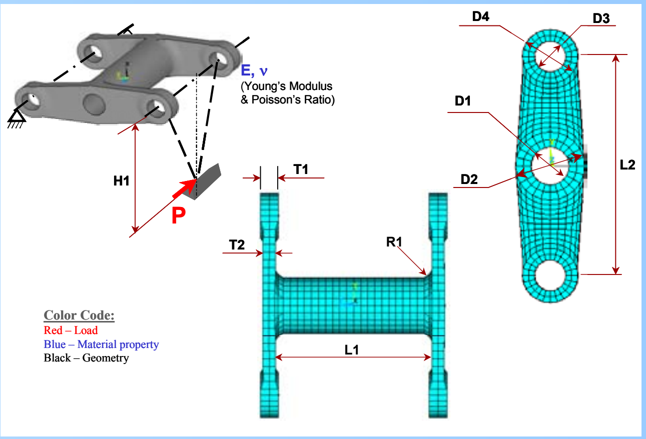
➢ Feasibility Study on Probabilistic Methods applications to damage tolerance analysis of a dynamic component:

Response Surface Method



Idler Link

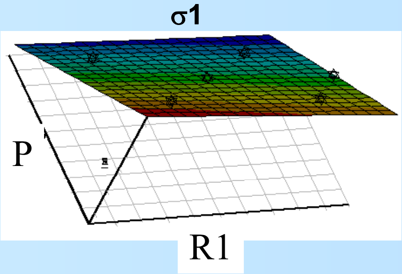




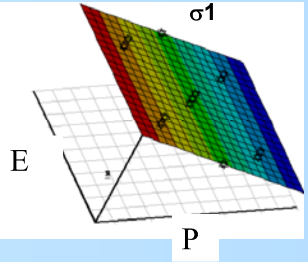
Parametric Model

Variables:

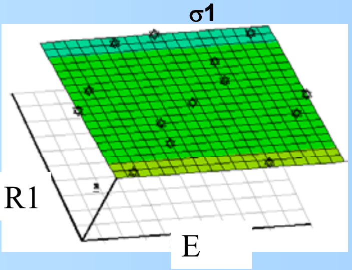
1. Geometric Variable, R1
2. Material Property Variable, E
3. Load, P



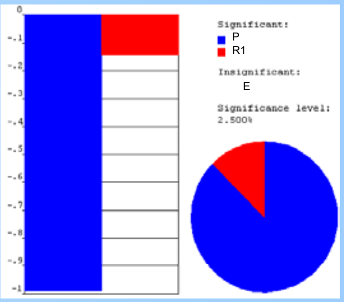
$\sigma_1 = f(P, R1)$



$\sigma_1 = f(E, P)$



$\sigma_1 = f(E, R1)$



Output parameter: σ1 at critical location

Sensitivity Analysis

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Bell - 2003 Technical Accomplishments

- RA 1: - RITA principals delivered a joint DT issues report
  - Defined the test plan and fabricated coupons for testing surface, through and corner cracks. Completed testing of CT coupons for crack growth threshold. Completed the design of element level coupon
- RA 2: - Developed a stress equation that includes beam and chord bending and tension, histograms, exceedances plots using four usage spectra for a main rotor yoke PSE
  - Collected Usage data on two B412 aircraft at PHI and also obtained Operational data for the Bell model CH-147 from Canadian Forces. Evaluated usage data obtained from PHI for two aircraft using Bell Usage Credit Software (BUCS) and defined enhancements for needed BUCS system to be compatible with current HUMS software release. Delivered a data package
- RA 4: - Developed crack growth threshold and da/dN data for 7075-T73 Al forging, 7050-T7452 Al forging using surface crack coupons, Kb bar. Developed crack growth threshold and da/dN data for through crack CT specimens of a main rotor yoke. Delivered a data package
- RA 5: - Compared NDI probes for detection of cracks under the fasteners and also investigated the effects of manufacturing processes, materials and environmental conditions. Designed the prototype panels for detecting cracks under in a tail boom.
  - Developed techniques will be evaluated by PHI (Beta Test Site operator). Delivered a data package
- RA 8: - Evaluated AGILE code using 5 generic problems and presented the results in workshop I. For workshop II, evaluated AGILE code using a rotorcraft component. Completed two reports and delivered a data package
- RA 9: - Completed case study of using Probabilistic Methods (PM) for rotorcraft component and delivered a data package

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Boeing Tasks/RCDT Roadmap Areas

TASK/AREA	2000	2001	2002	2003	2004	2005
Boeing Task 2/Road Map Area 2 Spectrum Development						
Boeing Task 3/Road Map Area 8 Crack Growth Analysis						
Boeing Task 9/Road Map Area 6 **Certification Testing**	Coupon Component					
Boeing Task 11/Road Map Area 1 **RCDT Specific Issues**						
Boeing Task 13/Road Map Area 9 **Risk Assessment**						
Boeing Task 8/Road Map Area 10 **Corrosion Control**						

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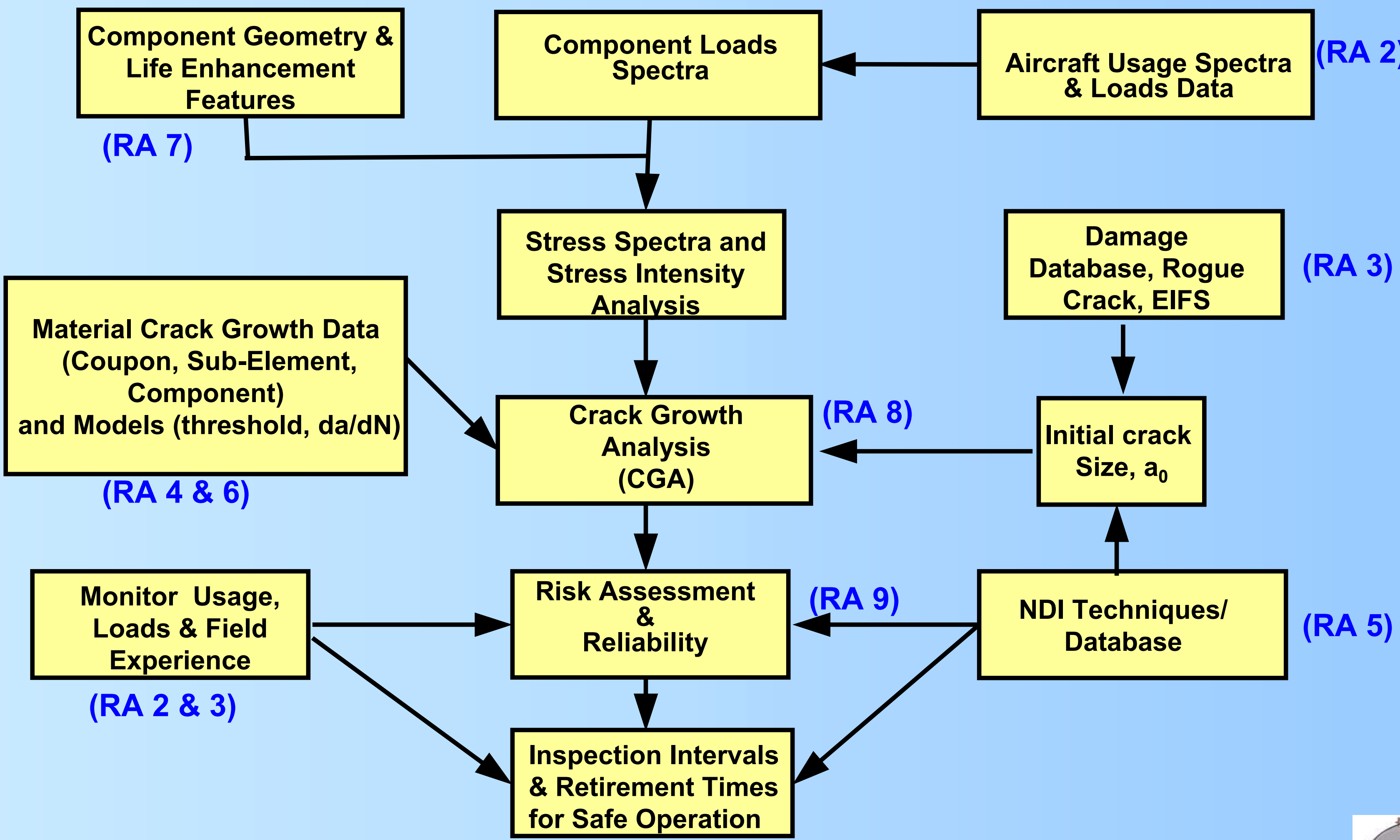
Task 11 RCDT Issues (Road Map Area 1)
Basic Elements of Crack Growth Methodology for Rotorcraft DT



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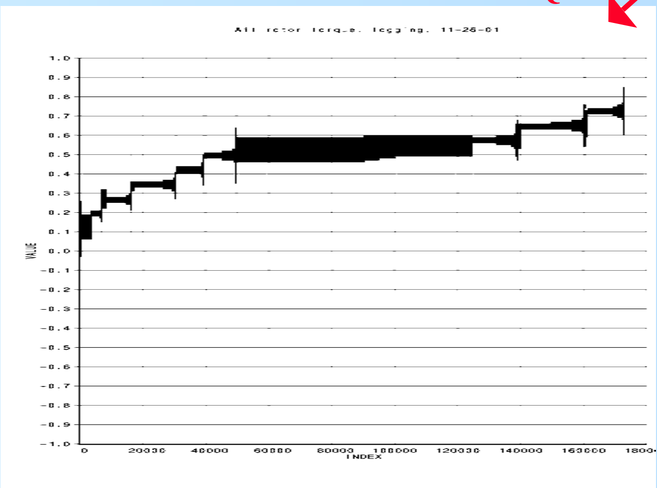
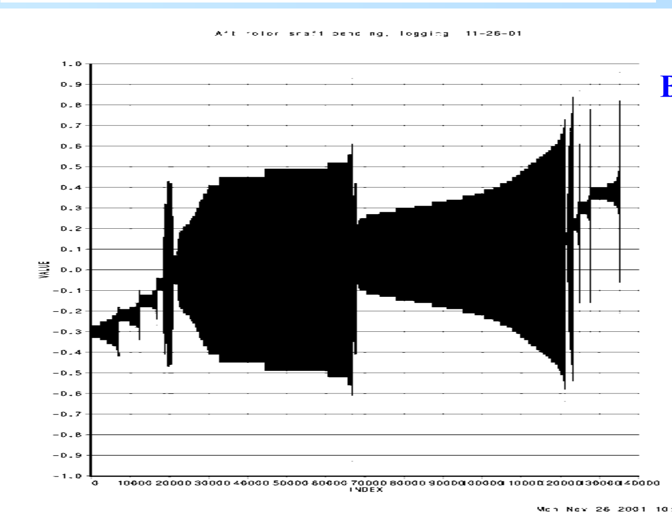
Task 2 Spectrum Development (Roadmap Area 2)

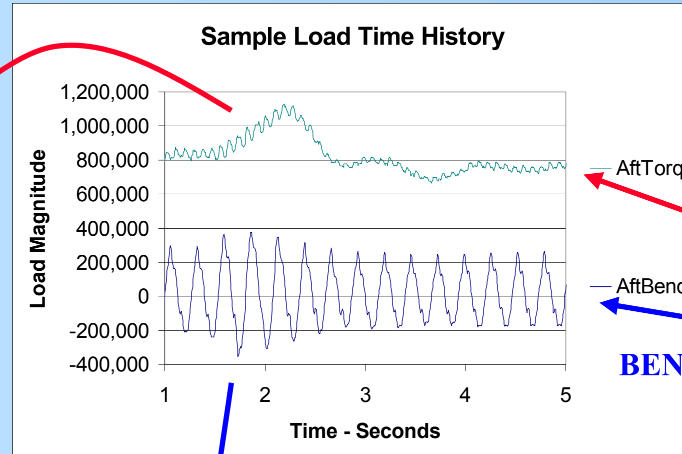
Normalized Load Spectra

TORQUE



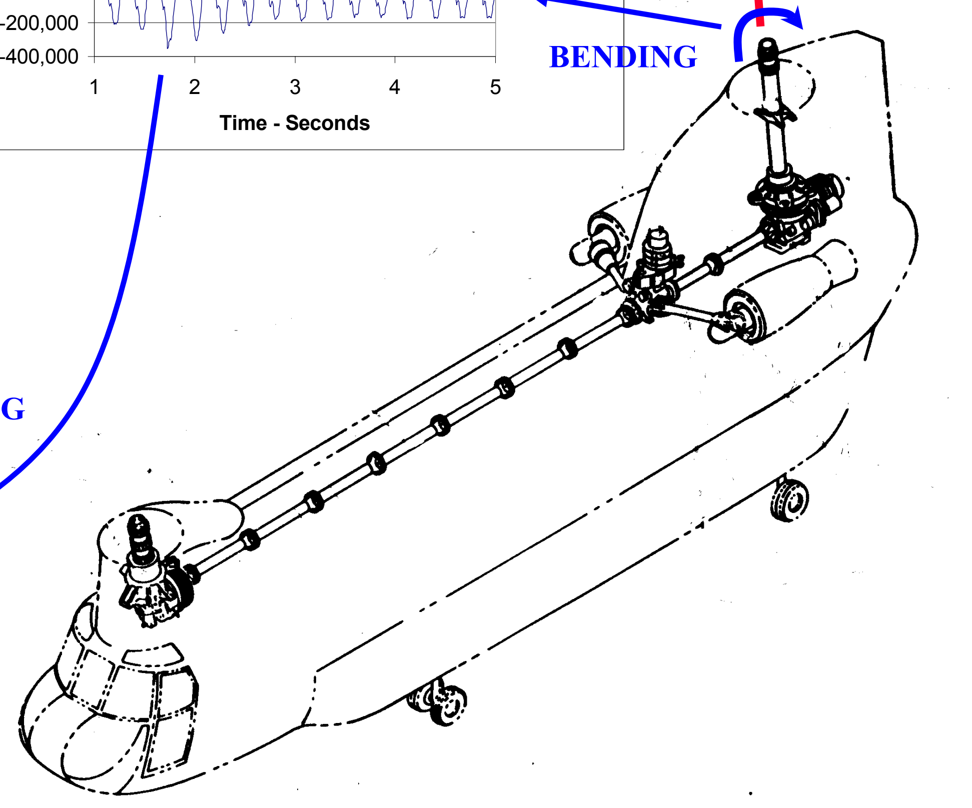
BENDING





TORQUE

BENDING



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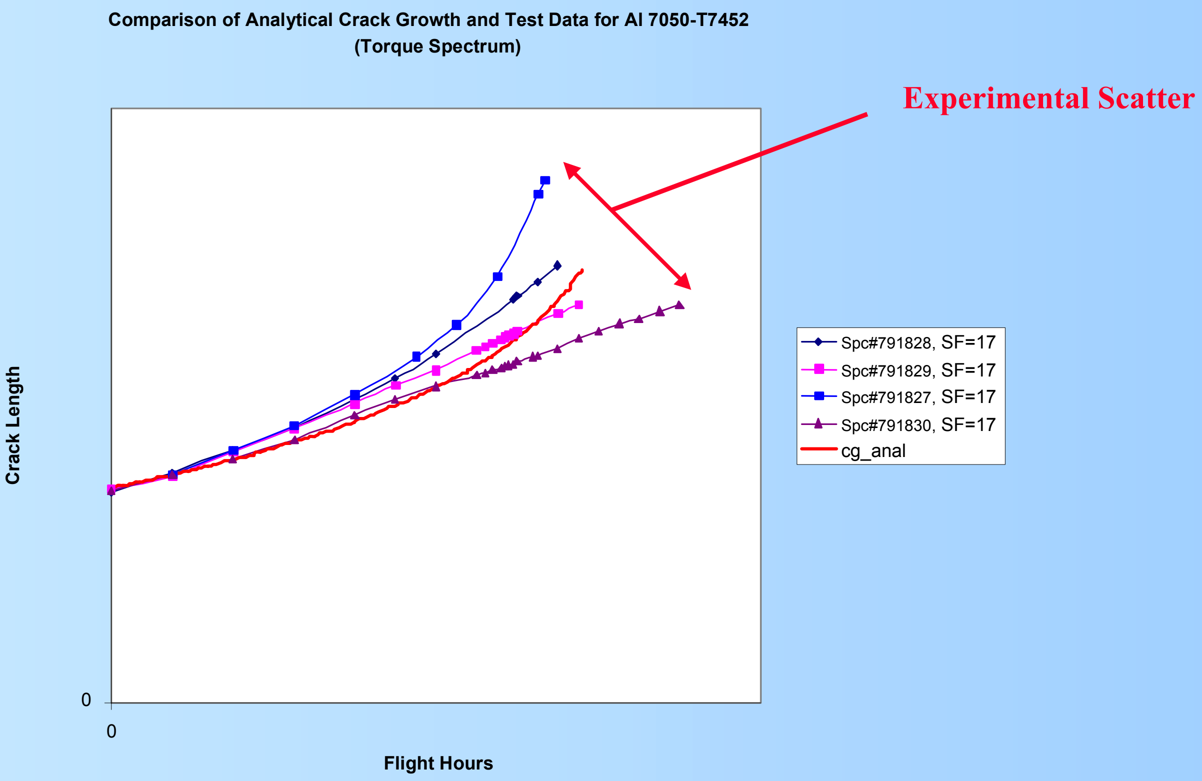
Task 9 Qualification Test Methods (Roadmap Area 6)

Approach Being Developed to Address Concerns with Sensitivity of Rotorcraft Crack Growth Analysis Results to Fits used to Model Material Crack Growth Properties as a Function of Load Ratio

- Conduct Multiple Coupon Tests Using a Selected Rotorcraft Load Spectrum.
- Conduct Crack Growth Analyses, Adjusting Fits to Material Crack Growth Properties Until Analytical Results Compare Favorably to Test Results.
- Conduct Additional Coupon Testing Using a Different Rotorcraft Load Spectrum with Different Load Ratio Characteristics.
- Conduct Crack Growth Analyses for Second Spectrum Using Material Crack Growth Property Fit from First Spectrum.

Task 9 Qualification Test Methods (Roadmap Area 6)

Sample Data Being Developed



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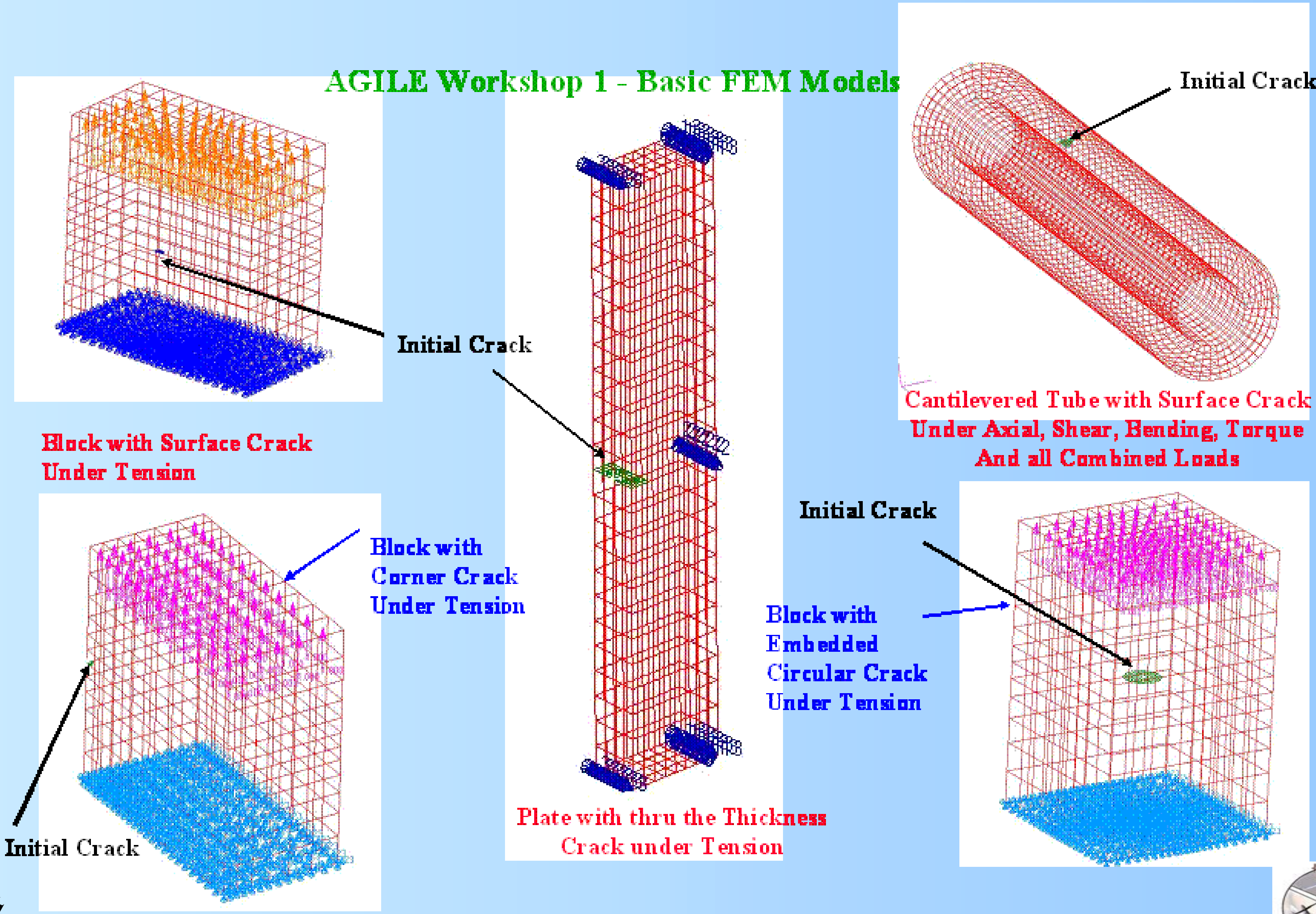
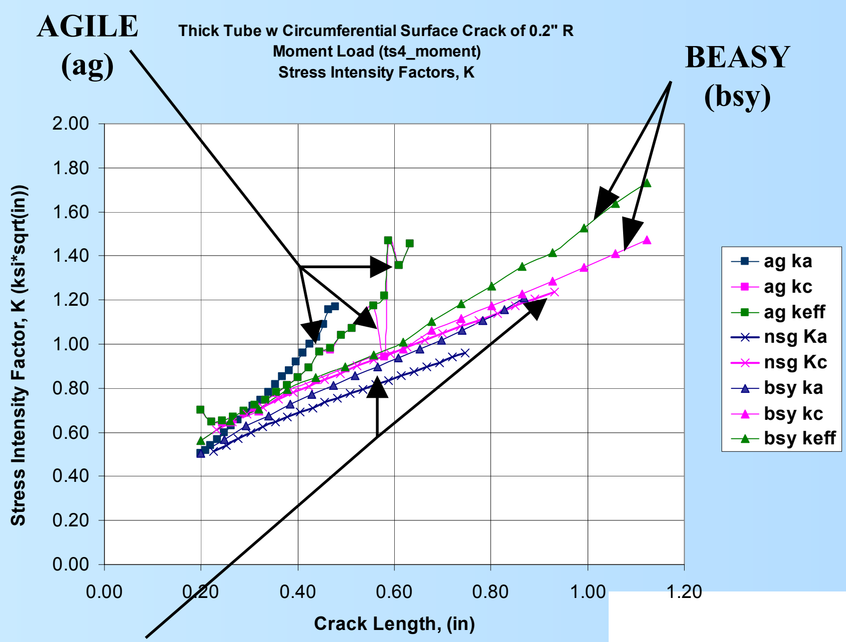
Task 3 Evaluate Crack Growth Analysis (Roadmap Area 8)



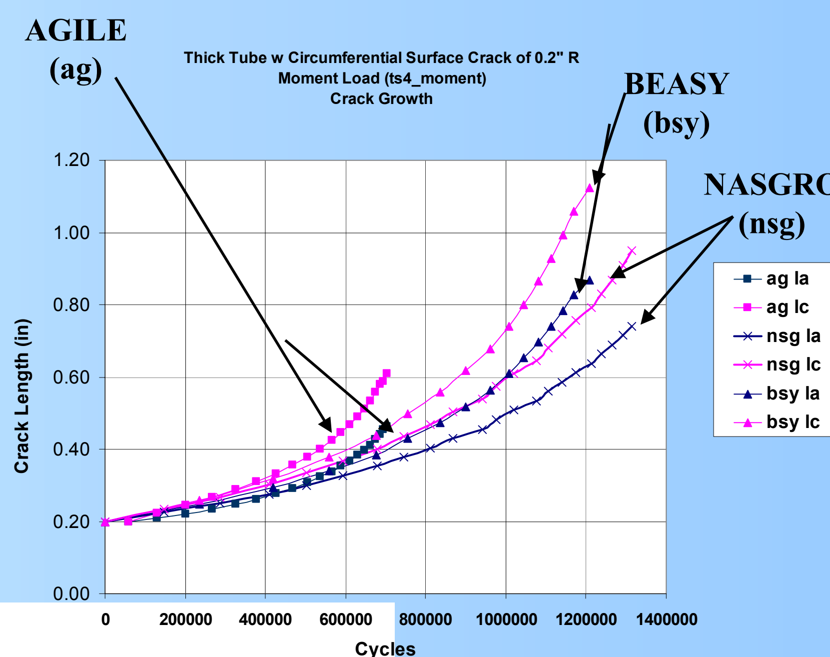
AGILE Workshop 1 - Typical Results

(Tube with Surface Crack under Moment Load)

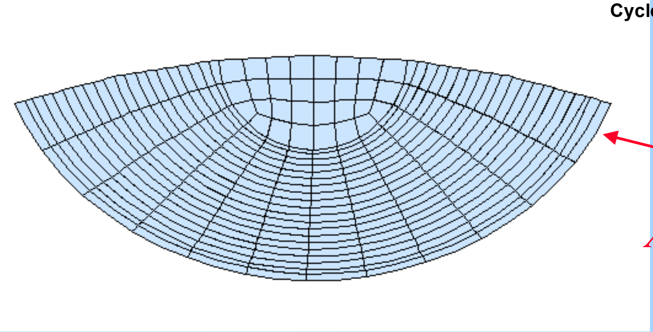
Comparison of AGILE, NASGRO and BEASY



SIF Plot



Crack Growth Plot



AGILE Crack Growth Shape

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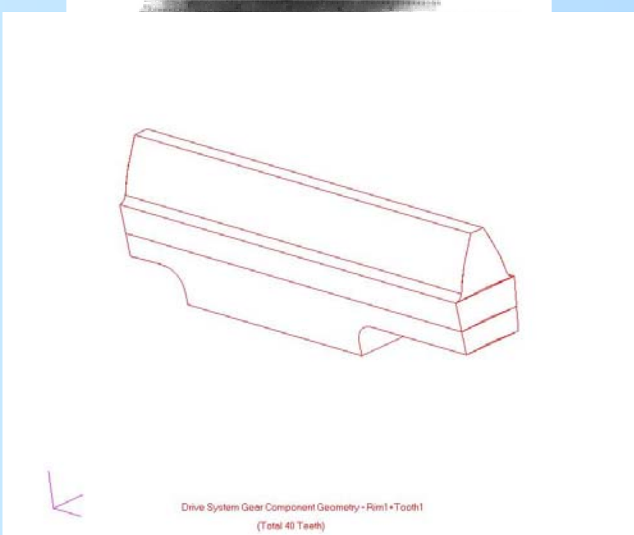
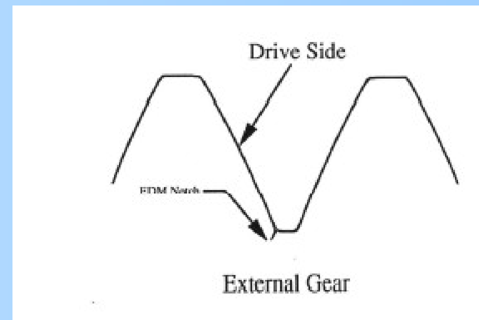
AGILE Workshop 2 - Rotorcraft Component Gear Crack Growth Analysis



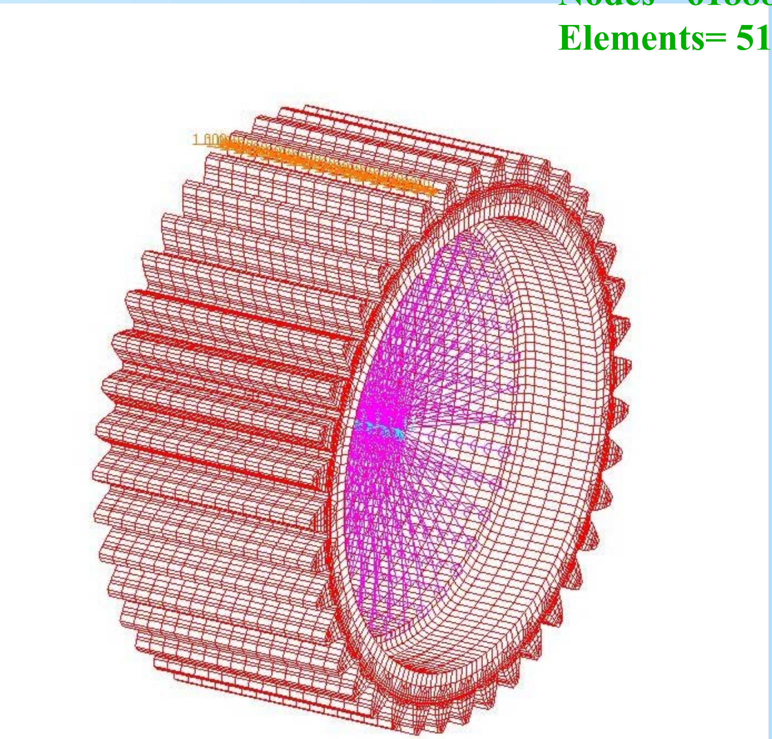


Location of EDM Notch & Initial Crack

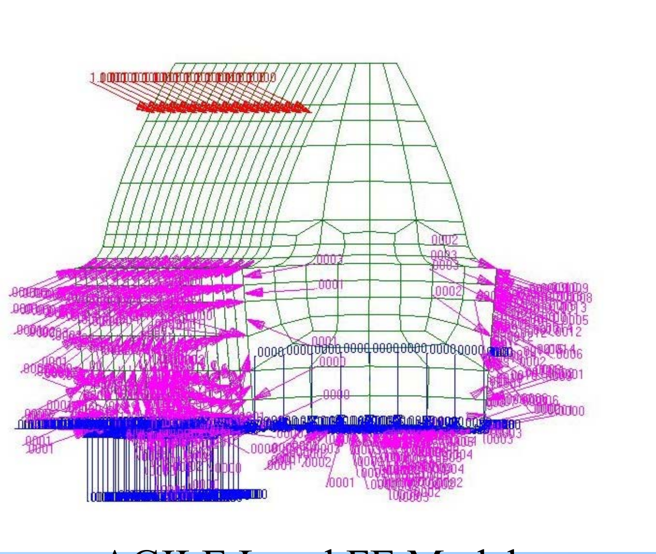
Gear with Broken Tooth

AGILE Global and Local Models of a Gear

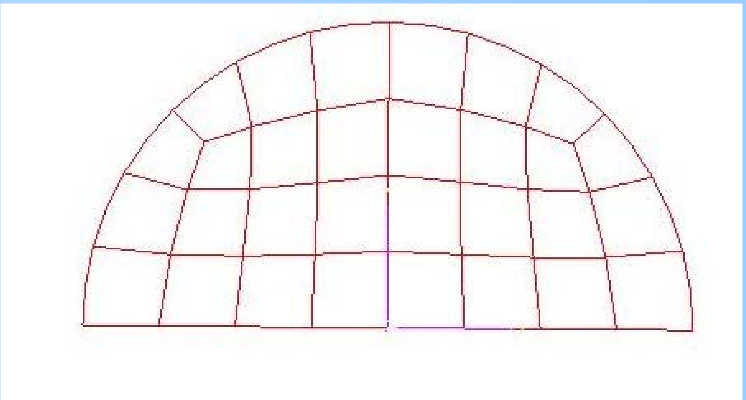
Nodes= 61888
Elements= 51689



AGILE Global NASTRAN Model



AGILE Local FE Model



AGILE Initial Crack/BEM Model

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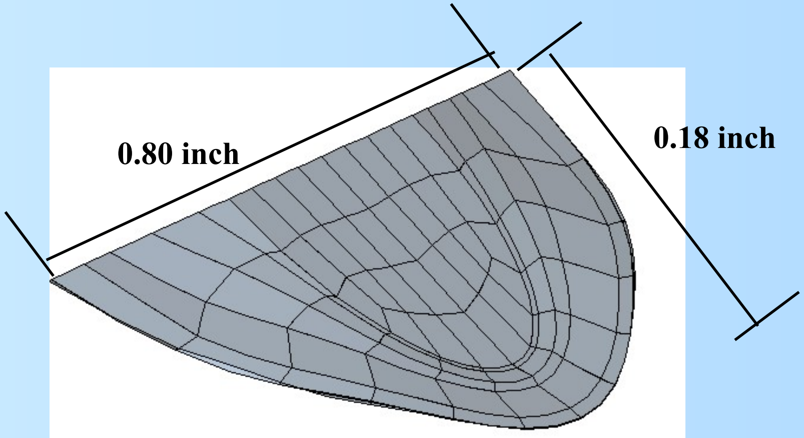
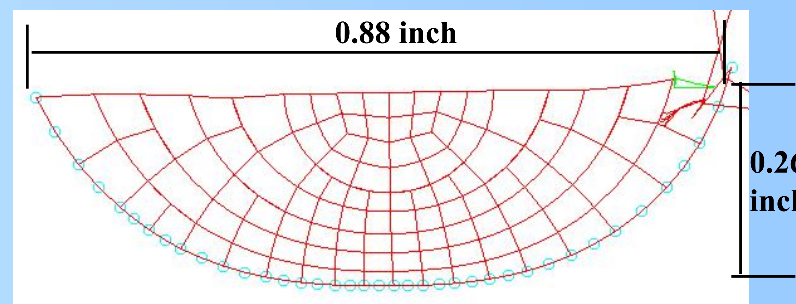
AGILE Workshop 2 - Gear CG Analysis Results

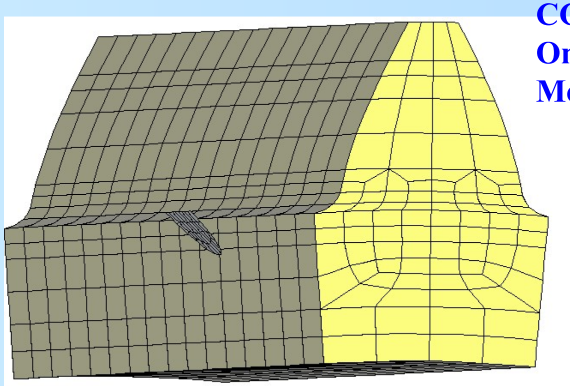
Predicted Crack Growth Shape in Gear Tooth



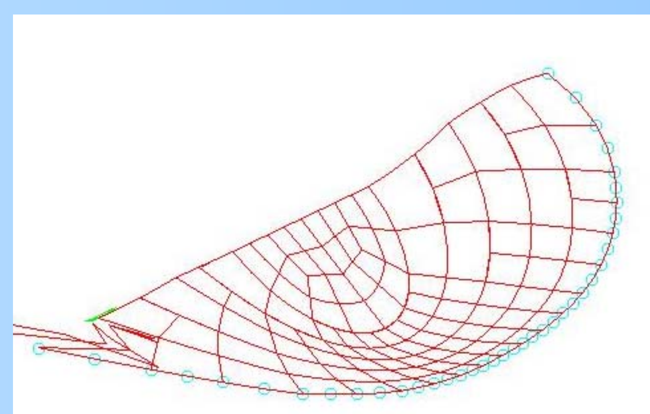
AGILE CG Shape



BEASY CG Shape



CG Superposed On Local AGILE Model



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AGILE Workshop 2 - Gear Analysis and Test

Uncertainties of Analysis:

• Loading:

- Multiple teeth in contact at any time
- Highest Point of Single Tooth Contact is assumed as the worst case maximum load
- Status of loading at other meshes is unknown when HPTC load is applied at the cracked tooth
- Minimum stress at the cracked tooth occurs when the load is on the adjacent tooth
- Load at all contact points at any instance is unknown

• Material Properties:

- Properties for the gear material are not available
- Material properties for 4340 Steel from NASGRO3 database used (C4DC21AB1)

•Test Data:

- Strain data not available for comparison of stresses
- Crack growth data is obtained from striation count by Material Laboratory

Observations/Conclusions:

• Crack growth analysis of the component is complex due to uncertainties of input data to models and lack of data from tests (such as strains, actual n vs. a).

• Comparison of analytically predicted crack growth shape and “n vs. Crack Length” by AGILE and BEASY are not good.

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Summary of Crack Growth Analysis Code Attributes – as of June 2004

(Roadmap Area 8)

Attribute/Code	**AGILE**	**BEASY**	**AFGROW, NASGRO**	**Cracks2000**
Type of Code - ***Stress Analysis*** ***K Calculation*** ***Crack Growth***	No Yes Yes	Yes Yes Yes	No Yes Yes	No Yes Yes
- ***Capability- 2D, 3D***	Yes	Yes	2D & Limited 3D	2D & Limited 3D
Stress Intensity Factor, K	FEM/BEM (Complex Geometry)	BEM (Complex Geometry)	Empirical Eqn. from Built-in-Library or User Input	Empirical Eqn. from Built-in-Library or User Input
Source - Stress Analysis	NASTRAN/ ANSYS and Local FEM/BEM	Self Contained BEM	User Supplied Stress Spectra Compatible with Stress Intensity Factor Expression	User Supplied Stress Spectra Compatible with Stress Intensity Factor Expression
Ease of Use	FEM Experience Required	FEM Experience Required	Usable by Experienced Engineer	Usable by Experienced Engineer

Summary of Crack Growth Analysis Code Attributes – as of June 2004

(Roadmap Area 8)

Attribute/Code	AGILE	BEASY	AFGROW, NASGRO	Cracks2000
Steps required for Complete Solution	One to Multiple, Varies with Complexity of Component	One Step; Multiple for Efficient Solution	One Step	One Step
Auto-Crack-Growth	Yes; K and crack growth solution indicate some instability	Yes; Solution Time Increases Exponentially with Growth of Crack	Yes	Yes
Modeling Time	Comparable to FEM Models	Comparable to FEM Models	Short, Limited to Less Complex Models	Short, Limited to Less Complex Models
Solution Time	Long for Large Complex Models	Long for Large Complex Models	Short	Short
Post Process Time	Significant	Insignificant	Insignificant	Insignificant
Computational Resources	Faster CPU, Large Disk Space, & Memory	Faster CPU, Large Disk Space, & Memory	Minimum	Minimum

Summary of Crack Growth Analysis Code Attributes – as of June 2004

(Roadmap Area 8)

Attribute/Code	AGILE	BEASY	AFGROW, NASGRO	Cracks2000
Proposed Plan for Verification	Validate K-solution with known Cases; Verify Crack Growth Under Spectra Load	Needed for Simple/Complex Geometry with Simple/Complex Loads	Needed for Simple and Complex Loads	Needed for Simple and Complex Loads
Problems/Bugs	Spurious spikes and bums in predicted SIF curves which may affect crack growth; Difficulties in predicting crack growth for non-planer cracks; Crack aspect ratio (a/c) does not agree well with BEASY and Test Data; Questionable results for combined loads; Can't handle through cracks, multi-front cracks, and cracks in which only one end grows; No interaction models; No multi-axial loading option; Can't solve cracks which are partly in compression; Solution time increases exponentially as the crack grows; Local model size is limited to about 1500 to 3000 elements	Crack adder used in Version 9.0 does not function properly, and aborts run prematurely for some gear problems; Computation of K for torque loads are based on maximum K instead of ΔK range; Can't handle cracks which grow on one side only; Solution time increases exponentially with number of elements on the crack; Model size is limited to about 10000 to 12000 elements	Needs Further Development/ Improvements	Needs Further Development/ Improvements

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Summary of Crack Growth Analysis Code Attributes – as of June 2004

(Roadmap Area 8)

Attribute/Code	AGILE	BEASY	AFGROW, NASGRO	Cracks2000
Proposed Updates/ Improvements	Resolve problems/bugs; Implement NASGRO-4.02 CG Law and Inter-action Models; Update Manuals	Resolve problems/bugs, Implement NASGRO-4.02 CG Law; Improve Code and Crack Wizard Efficiency	Implement Recommendations of NASGRO Consortium	List not Developed
Recommendation Based on Limited Evaluation	Validate with additional complex rotorcraft subjected to complex loading before use	Analyze Simple or Complex Problems, Recommended for complex geometries and loading	Use where Built-in K Library Cases Adequately Define the Problem	Use where Built-in K Library Cases Adequately Define the Problem

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Accomplishments during 2003 project year:

Administration & Coordination-

- Held weekly telecons for technical coordination
- Supported FAA Funded Projected Investigating threshold test methods at NASA Langley (Heat treated and rough machined 9310 specimens)
- Attended technical meetings (At RITA year end review in March 2004 and at AHS Forum in June 2004)

Crack Growth (CG) Analysis-

- Prepared for and participated in AGILE Workshop 1 (Basic geometries)
- Prepared for and participated in AGILE Workshop 2 (Boeing Gear Problem)
- Updated chart showing comparisons of CG codes

Certification Testing-

- Completed coupon testing for torque spectrum and partially completed bending spectrum for a forged aluminum alloy.

RCDT Issues-

- Completed Interim Issues Document (team document)
- Started Final Issues Document

Documentation-

- Completed Interim Technical Report (approved for public release)
- Completed Data Packages
- Completed Updated Interim Technical Report (public release pending)

Sikorsky Tasks/RCDT Roadmap Areas

Roadmap Area	Task Title (Project Year)	00	01	02	03	04
1	RCDT specific issues study					
3	Damage Database & EIFS					
4	Crack growth rate database					
5	Non-Destructive Inspection					
6	Certification Testing					
7	Life enhancement methods			AACE Project		
8	Crack growth analysis					
9	Risk assessment					
10	Corrosion Control					

Blue Text: indicates 2003 tasks

2003 Sikorsky Technical Objectives

RA 1: Identify Rotorcraft Damage Tolerance Specific Issues and Supporting Joint RITA Issue Report.

RA 3: Create Damage Database for Historical Data on Causes for Premature Removal of Rotorcraft Parts, and Relate Historical Damage to Equivalent Initial Flaw (Crack) Size (EIFS).

RA 4: Collaborative Effort With NASA/LARC and NASA/JSC to Develop Crack Growth Rate Test Methods Especially for Threshold Crack Growth Rate Data & Models for Common Rotorcraft Materials

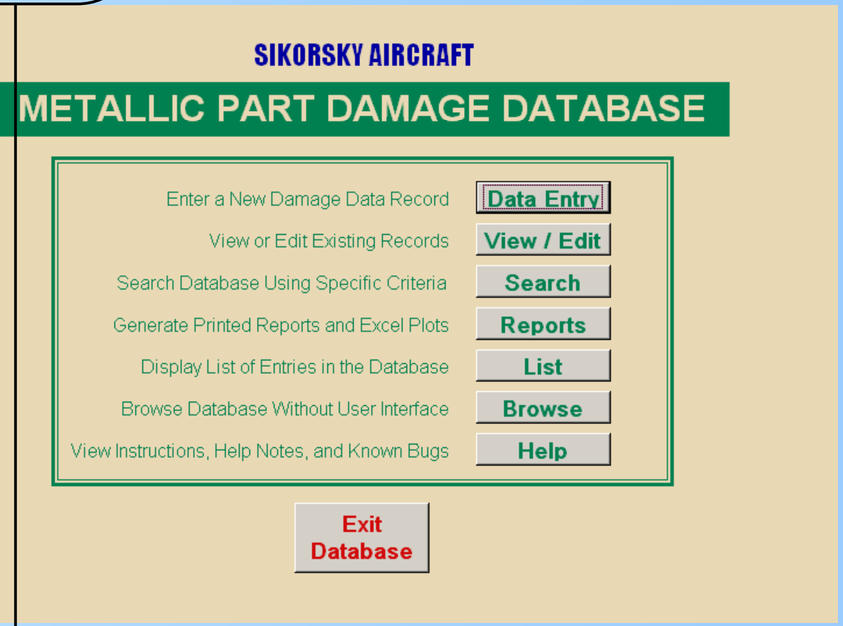
RA 5 Evaluate NDE Techniques for Small Crack Detection and Assess DT management Costs of Rotorcraft Components.

RA 8 Evaluate / Validate Fracture Mechanics and Crack Growth Codes and Perform Damage Tolerance Case Study for Rotorcraft Components.

RA 10 Identify Primary Types of Rotorcraft Corrosion, Investigate Potential Corrosion Sensor Technologies, and Develop Corrosion Control Strategies

Roadmap Area 3: Damage Database & EIFS

Updated Damage Database Documentation



Recorded Historical Data in Damage Database used to determine EIFS in CGA

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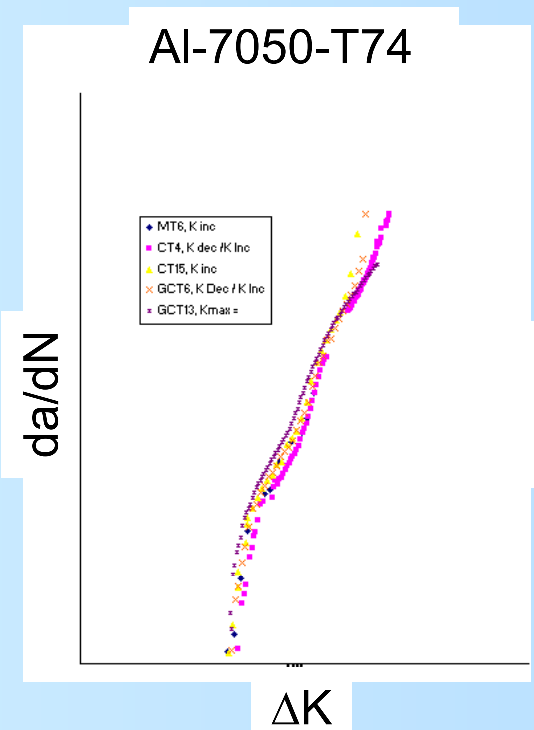
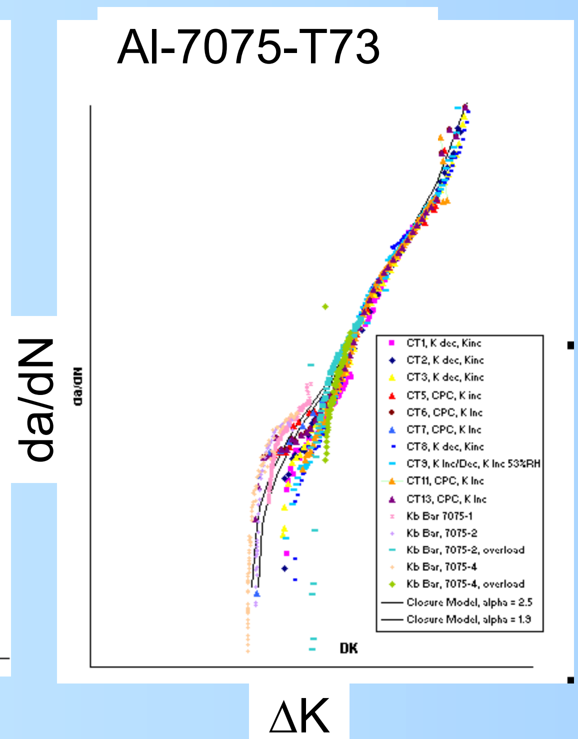
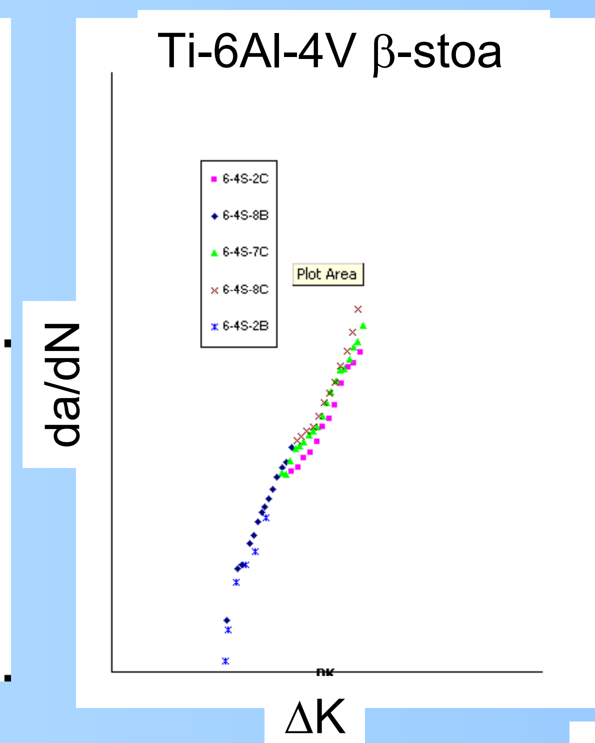
Roadmap Area 4: Crack Growth Data

- Significant improvement threshold characterization
- Sample of High R value cg data in report and data packages
- Interacting with NASA Langley to improve threshold test methods
- Data useful to update crack growth characterization in NASGRO







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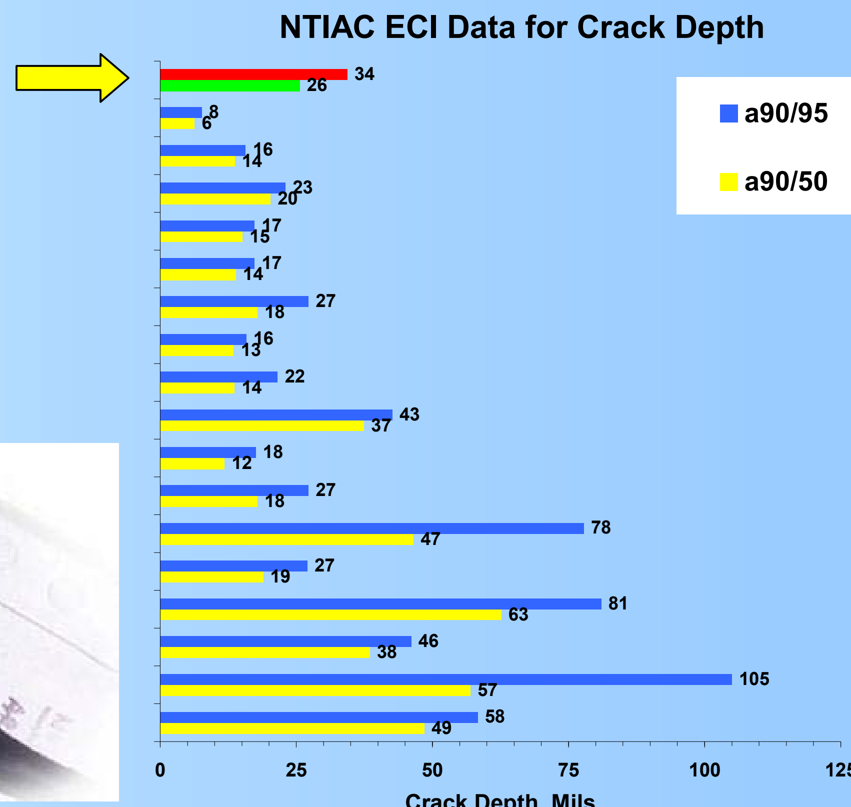
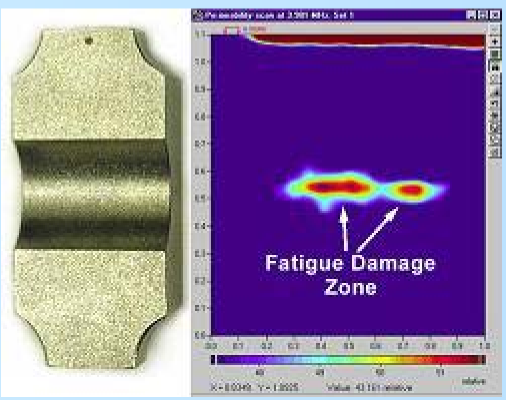
Roadmap Area 5: NDE and DT Assessment

- Evaluated Potential NDE Methods for Capabilities for Detection of Small Cracks in Rotorcraft Structure

<u>Mature Technologies</u>
- •Eddy Current (automated+conventional)
- •Fluorescent Penetrant
- •Magnetic Particle

<u>Emerging Technologies</u>
- •MWM Eddy Current Sensor Arrays
- •Pulse Thermography NDT
- •Thermosonic (Thermography + Ultrasonic)





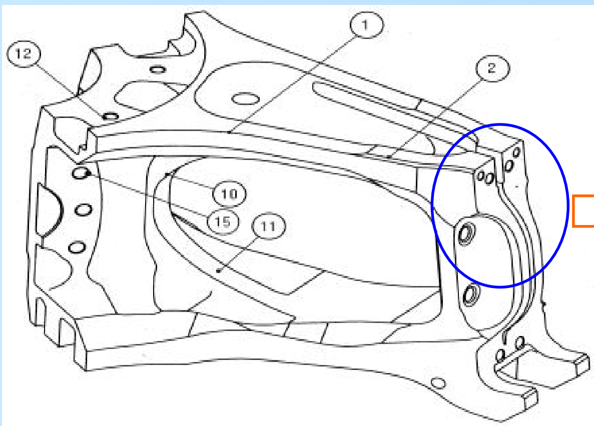
Surface mounted MWM EC sensors (JENTEK Inc).

- For select components, ECI crack detection capability has potential for DT assessment. Also MWM ECI sensor has potential for crack monitoring

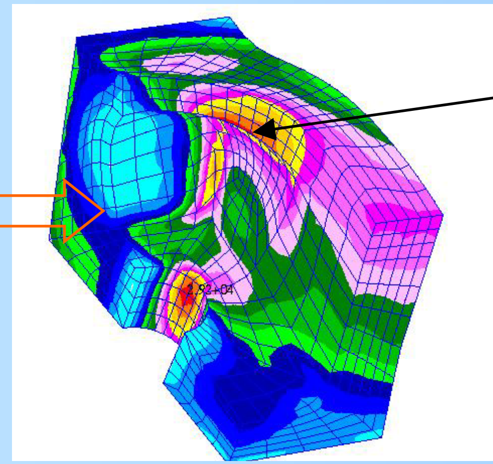
Roadmap Area 5: NDE and DT Assessment

Evaluation of NDE Inspection Interval and Costs for Selected Components

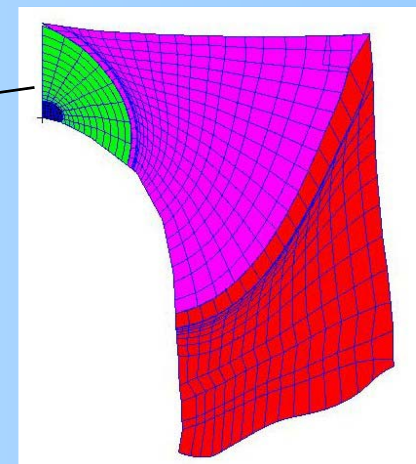
Component



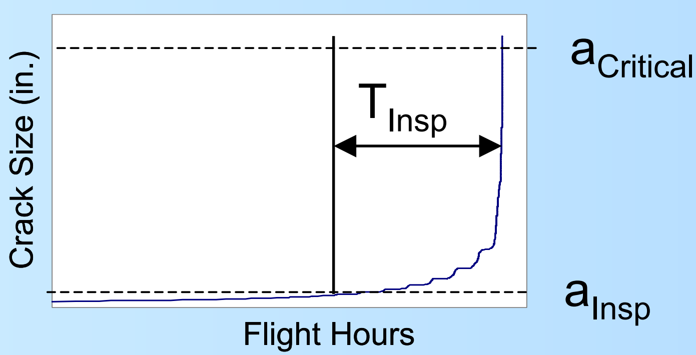
Local



Local Model



Inspection Interval



Inspection Cost

$$
\begin{aligned}
E(c) = {} & K1 \times N \times C_i(inspection) \\
& + K2 \times N \times P(\Delta a_1) \times C_{r_1}(repair) \\
& + K3 \times N \times P(\Delta a_2) \times C_{r_2}(replacement)
\end{aligned}
$$

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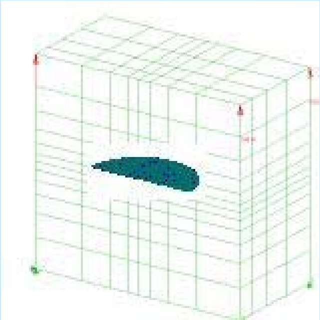
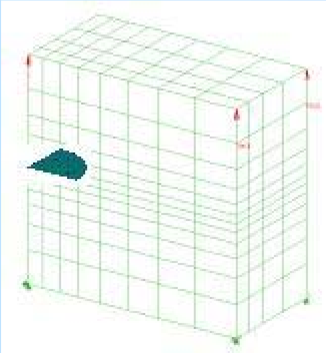
Roadmap Area 8: Crack Growth Analysis Methods

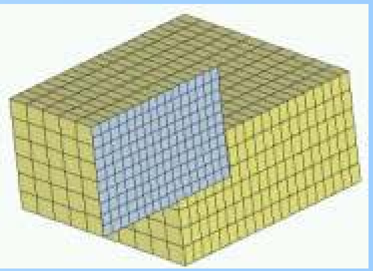
AGILE Workshop I: Generic Crack Growth Problems



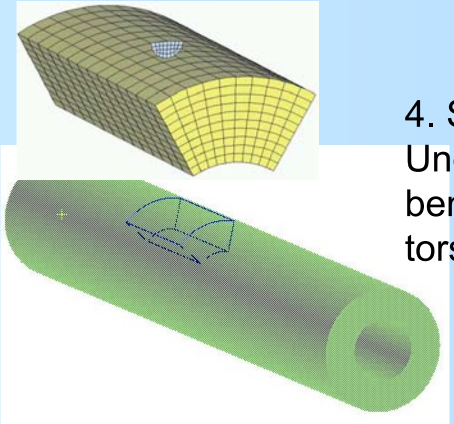
1. Surface crack
Under tension



2. Corner crack
Under tension

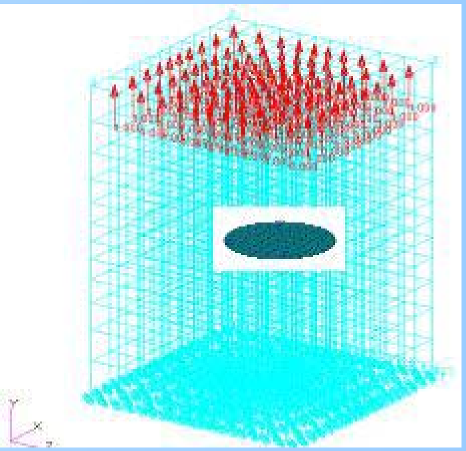


3. Through crack
Under tension



4. Surface crack
Under tension,
bending, shear,
torsion, combined.

5. Embedded
Crack Under
tension



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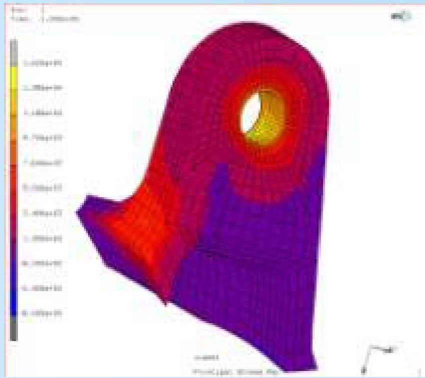
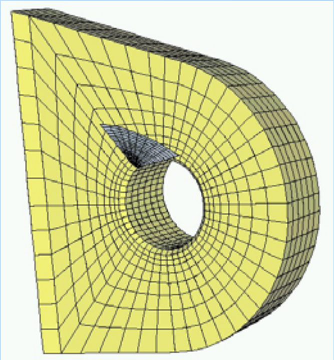
Roadmap Area 8: Crack Growth Analysis Methods

AGILE Workshop II - Specific Rotorcraft Problem

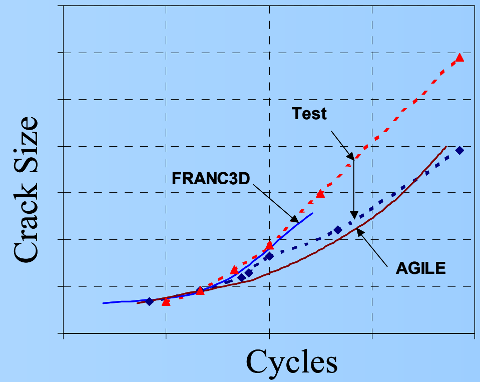
MR Hub Damper Lug – (Good correlation with crack measurement)



Stress in Global Model

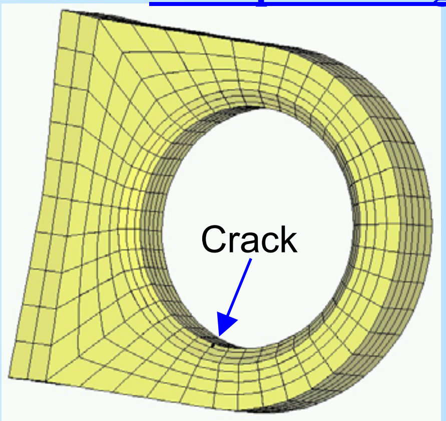


AGILE Local Model

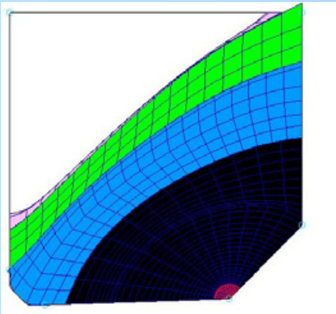


Crack Growth Test and Analysis

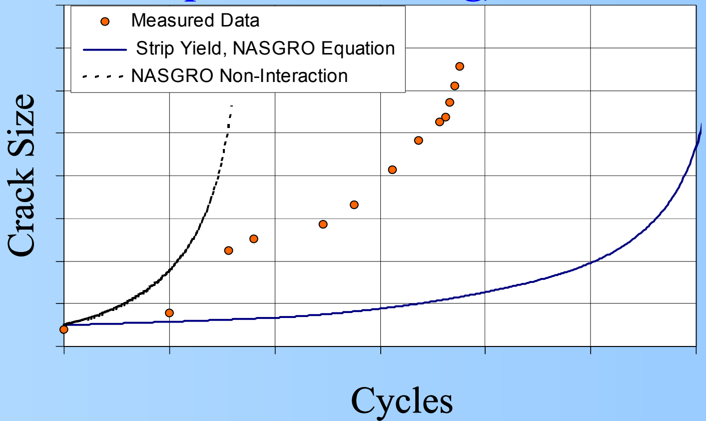
MR Spindle Lug – (Discrepancy may be attributed to spectrum loading)



AGILE Local Model



predicted Crack



Crack Growth Test and Analysis

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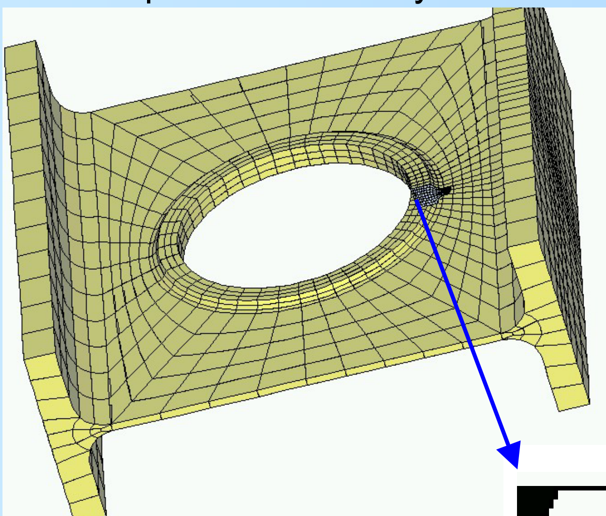
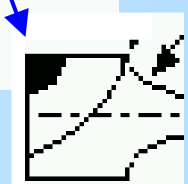
Roadmap Area 8: Crack Growth Analysis Methods

Case Study: Cranfield Damage Tolerance Round Robin Problem

Component Geometry

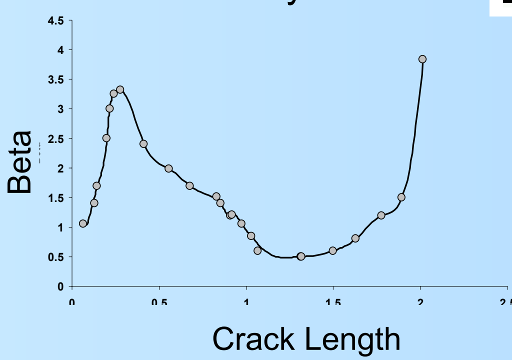


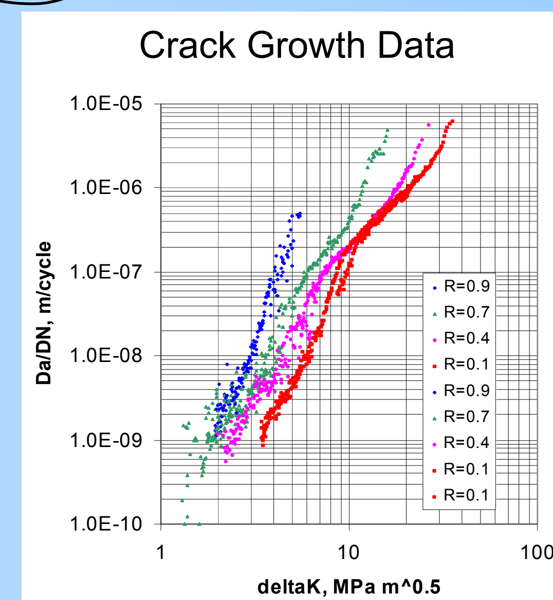


Normalized ASTERIX Spectrum

cycles	max	min	cycles	max	min
36000	0.92	0.76	14186	0.84	0.68
1	0	-0.04	36000	0.92	0.76
8	0.32	0.28	234	0.88	0.64
140	0.44	0.4	434	0.88	0.68
14186	0.52	0.36	201	0.92	0.64
140	0.48	0.44	83	1	0.56
346	0.52	0.44	260	0.84	0.76
139	1	-0.04	25266	0.88	0.72
346	0.6	0.56	289	0.92	0.68

Stress Intensity Solution





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Roadmap Area 8: Crack Growth Analysis Methods

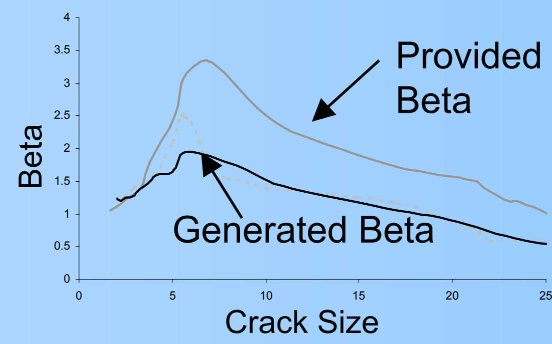
Rotorcraft Airframe Structural Case Study

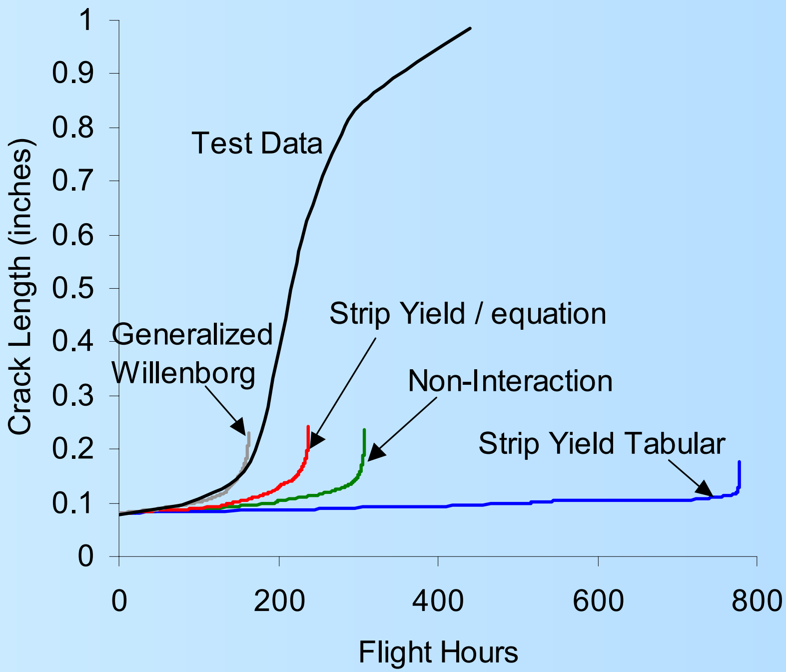
<u>Phase I Analysis:</u>

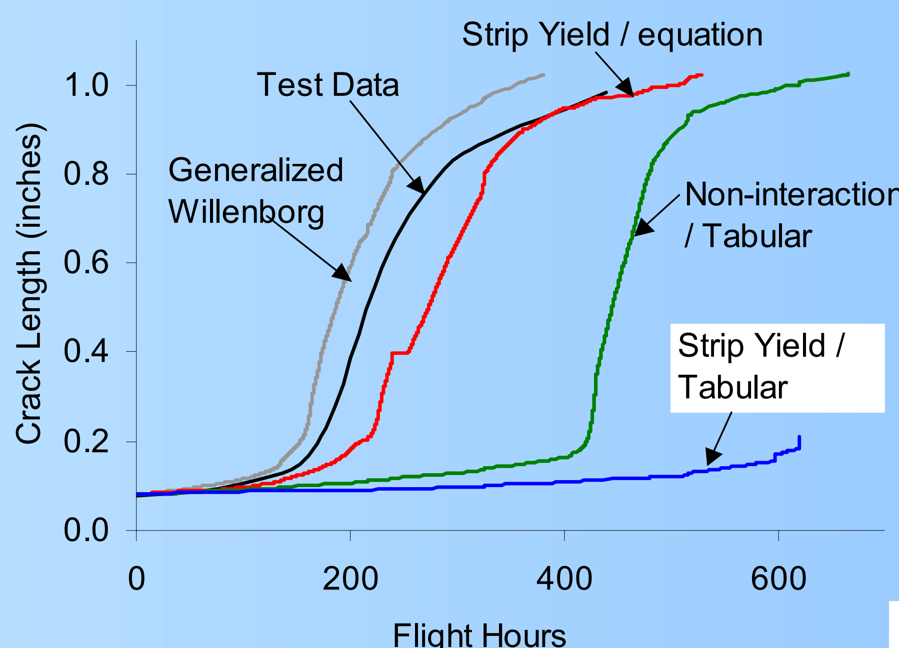
Using provided stress intensity, material data, and spectrum, Performed NASGRO crack growth analysis with various models

<u>Phase II Analysis:</u>

Generated stress intensity solution, and Performed NASGRO crack growth analysis with various models







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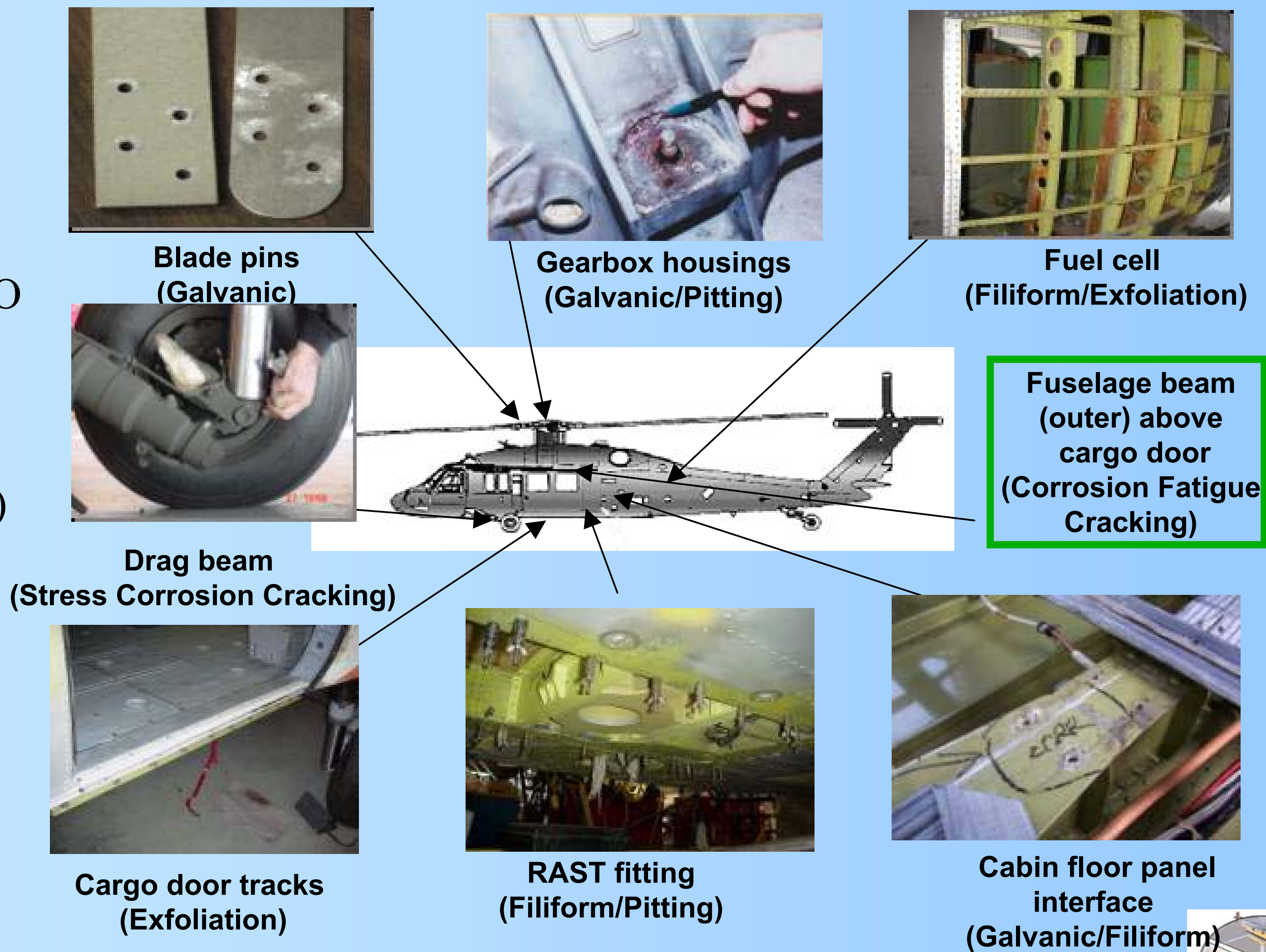
Roadmap Area 10: Corrosion Sensors

Corrosion Cost and Types

Corrosion Costs

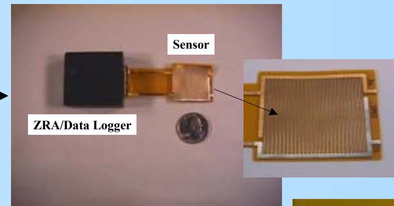
- Military assets ~$20B/year (GAO Rpt 2001)
- DoD Rotorcraft ~$4B/year (1998)
- Corrosion costs ~15% of total maintenance cost (Navy H-60)

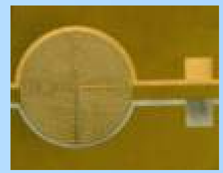


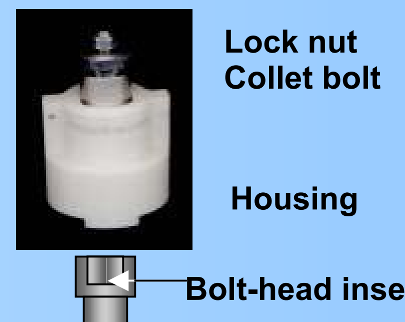
Roadmap Area 10: Corrosion Sensors

State-of-Art Corrosion Sensor Technologies

EXTRINSIC SENSORS
- Galvanic
- NDE
- EIS
- Resistance
  - Ionic
  - Electrical

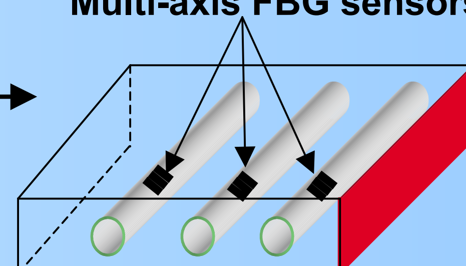




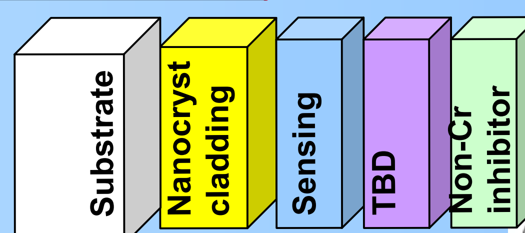


Estimated ROI ~9%

INTRINSIC SENSORS
- Optical Fiber with “smart” coatings
- Embedded Fiber Bragg Gratings
- Fluorescent paint coatings



- Multifunctional “smart” coatings
  - Sense---report
  - React---self-repair
  - Directed repair (2-way response)
    - Fiber optic array



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2003 Technical Accomplishments:

RA 1 In Coordination with Bell and Boeing, Developed the DT Flow Chart and Reviewed Boeing's Issue Report.

RA 3: Updated Metallic Component Damage Database Documentation.

RA 4: Reviewed NASA Rotorcraft Material Test Matrix and Objectives and Provided Feedback. Interacting with NASA on Testing Progress.

RA 5: Assessed Potential NDE Methods, Capabilities, and Costs for Detection of Small Cracks in Rotorcraft Structure, Determined Inspection Intervals for Selected Components

RA 8: ★ Evaluated AGILE CG Code with Five Generic Crack Problems. Performed CG Analyses of Two Full Scale Parts. Conducted Airframe Case Study of the Cranfield DT Round Robin Problem.

RA 10: Defined Primary Types of Rotorcraft Corrosion and Potential Corrosion Sensor Technologies, Strategies and Benefits.

Report: Interim Technical Report and Data Packages: Damage DB, CG Data, NDE, Life Enhancement, Agile Evaluations, CG Case Study, Corrosion.

ACKNOWLEDGMENT

We acknowledge the support from the NRTC and the FAA

NRTC

RITA Inc